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SCIENCE TO-DAY

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SCIENCE TO-DAY

A Brief Study of some of the Problems and Theories of To-day's Chemistry and Physics

BY

P. J. LANCELOT SMITH
M.A.(Oxon.), F.I.C., F.R.S.E.
Senior Science Master, Loretto School

AND

S. J. DALE, M.A., B.Sc.(Oxon.)
Assistant Master, Loretto School

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PREFACE

The present book is an attempt to deal with some of the problems and discoveries of Chemistry and Physics to-day, in such an elementary manner as to furnish a course suitable for the use of boys in upper forms not specializing in Science, and whose time for science work is restricted.

Accordingly, the experimental part of the book is designed solely to illustrate the text of the chapters. In order to maintain a continuity in the reading, experimental directions are given at the end of each chapter.

The Committee on the Position of Natural Science in Education state in their report that the work appropriate for boys not specializing in Science cannot aim at a great measure of completeness; that there is not time for extensive laboratory teaching. It is hoped that the course provided will serve to the non-specialist and the general reader as some introduction to present-day work in Chemistry and Physics.

We have striven to avoid a journalistic account of modern theories. We have therefore emphasized the methods by which knowledge has progressed, and drawn a distinction between observed facts and the hypotheses derived from them. Such difficult matters as the Quantum Theory and the Theory of Relativity are omitted, as an adequate treatment of them is beyond the scope of an elementary course.

Those sections involving mathematical calculations which are subsidiary to the main course are printed in smaller type.

We make no apology for introducing an account of the early Greek philosophers, as such a link with the past is an aid to realizing the problems of the future.

The radio-active material required for experiments in Chapters X and XI may be obtained from Messrs. J. J. Griffin & Sons, Ltd., Kemble St., Kingsway, London, who have arranged to make up small lots of the material (price 5*s*.).

We have to thank the Cambridge Instrument Company and Messrs. J. J. Griffin & Sons for the loan of blocks, also the Editors of *Nature* and the *Philosophical Magazine* for permission to reproduce photographs.

P. J. LANCELOT SMITH.

S. J. DALE.

LORETTO SCHOOL.

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SCIENCE TO-DAY

CHAPTER I

EARLY THEORIES OF THE GREEK PHILOSOPHERS

The object of modern science is the gaining of knowledge of the natural objects surrounding us, and of the laws governing these objects and their changes. Science deals with those things which make their direct appeal to the senses; indeed, it is through the agency of the latter that our knowledge, in the first place, is gained.

The sifting of evidence is the first business of science. This is not all that science has to do, as we shall see later, but failure to realize its great importance was the cause of its slow advance—from the time of Thales to that of Robert Boyle.

Knowledge of our surroundings is ever increasing; with that increase comes the need for specialization. A study of the materials of which objects are composed and of the laws which control their constitution is the science of chemistry; whilst the investigation of properties common to all kinds of matter, such as conductivity, density, power of refracting light, &c., is the province of physics. It is with the problems of these two sciences that we are concerned.

The human mind has always speculated upon the

cause of the phenomena of nature. These phenomena are forced upon our notice; the changing seasons, the sea and sky;—and the earth beneath us, of what is it constituted, and how is its structure maintained?

Naturally these questions would occur to the earlier inhabitants of the world. Some accepted the inevitable and without further inquiry gave themselves up to worship the forces of nature—*omne ignotum pro horrifico*. Of the many attempts at explanation, the boldest, and those which had the greatest influence upon the development of science, originated in the school of philosophy in Miletus, the chief Ionic city of Asia Minor. It is to be remembered that scientific theory, dealing solely with physical phenomena, was unknown to the Greek philosophers. Their hypotheses were far more ambitious, they related to life and conduct and the mind. Confused with these was a distorted atomic theory, vague in the extreme, and not in the least resembling the later ideas about the atom upon which chemistry has been built. Whilst the Greek mind—always anxious for some new thing—wandered from the structure of the universe, through the laws of life and thought, to the discussion of a hereafter, modern science sets itself the smaller task of finding a system by which phenomena associated with matter can be explained.

To say that modern discoveries concerning the constitution of nature were forestalled by the genius of Greek philosophers is untrue.

The age in which flourished the school of Miletus was an age of guessing. At a time when so many hypotheses were being put forward—when so many guesses were made—it is not surprising that some approximated to the truth. But we know that the natural sciences can be studied only by experiment. Jevons states in his *Principles of Science*: "When we change the course of

nature by the intervention of our will and muscular powers, and thus produce unusual combinations and conditions of phenomena we are said to experiment." This is what the early philosophers never did; manual labour was beneath the dignity of the schoolmen. Hence a curious anomaly—that while the names of the inventors of new hypotheses, or guesses, are kept historically intact, those of the discoverers of actual facts are not so preserved.

We begin a study of the Greek natural philosophers with a notable exception to the above statements. Thales of Miletus discovered that amber (ἤλεκτρον) when rubbed attracted light particles. What bearing this discovery had upon his theory of the constitution of matter it is difficult to state. He assumed the existence of one kind of matter which could be transformed into all other substances, and that, owing to this power of undergoing change, matter had life. In this connexion, it is remarkable that the idea of matter in modern physics has been replaced by electricity. Was the electric charge which Thales obtained from amber that one primordial something which he had in mind when he brought forward his hypothesis of one kind of matter endowed with life?

This belief in one single kind of matter was held by Anaximander (611–547 B.C.) and Anaximenes—another representative of the same school. According to Aristotle, they were not all agreed upon the one primal element. Thales finally pronounced it to be water, "considering all things to be full of gods"; whilst for Anaximander the fundamental principle was "the Infinite", a substance all-pervading and eternal, and capable of infinite extension—τὸ ἄπειρον.

Philosophers were still left guessing about this one unchangeable principle. To Pythagoras and his school

—a society, partly religious and partly political, which appeared in the Italian colonies of Greece at the end of the sixth century B.C.—number was the one thing permanent. So sure were they of such permanency that they stated that the number of heavenly bodies was ten—the perfect number. Aristotle points out that there were but nine that could be seen, and they fain must invent the tenth. At this time there arose the idea of emptiness, void. The Pythagoreans laid great stress upon it; it entered into their scheme of the universe, this idea of unlimited space, admitting a correspondence in their picture to the endless series of numbers. It seems strange to modern minds that the existence or non-existence of empty space could be argued about by the logicians without ever once making an appeal to experience or the evidence of experiment. Nevertheless, in spite of great advances in experimental science, the question, what is empty space? is still with us.

There arose two conflicting schools, one of which—the Eleatics, with Xenophanes as its founder—declared that the fundamental principle was " being ". They affirmed the eternity of all existence, for destruction would mean non-being; for the same reason there could be no such idea as void, and if there were no void no motion could be possible. On the other hand, Heraclitus of Ephesus believed that all things are in a state of perpetual flux; permanence was impossible—mobility was the essential, the mobility of fire. In these two schools was shown the usual Greek subtlety—skill in dealing with abstract thought, but as a genuine contribution to the advancement of knowledge its value is insignificant.

Empedocles (490 B.C.) should be mentioned, for, through Aristotle, his thought was to dominate science till the end of the seventeenth century. He considered that matter was made up of four essentials: fire, air, water, and earth.

These are principles which are indestructible and unchanging. The conception of Thales of one kind of matter had been abandoned by Empedocles for the four elements. Anaxagoras (500–427 B.C.) carried the idea of elements to a more rational conclusion. He assumed that there were as many elements as there are simple substances; these simple materials by repeated division yield minute *parts resembling the whole in properties.* Here is a much nearer approach to our ideas and discovered facts. Destruction consisted in the separation of the minute particles of the elements; their coming together what we should term chemical combination. Anaxagoras did not believe in void, or that there was any limit to the subdivision of particles. Furthermore, he believed that the subdivision and combination of the elements was brought about by an intelligence—the νοῦς, independently existing.

This assumption of an external intelligence separates the philosophy of Anaxagoras from that of the materialists who followed him; though undoubtedly his ideas about the subdivision of elements prepared the way for the atoms of Democritus. The latter philosopher was born in Thrace, and lived about 460–360 B.C. He was a great traveller and mathematician; he had spent five years with the Egyptian experts, from whom, possibly, he derived his ideas of atomic structure. His teaching was not well received, but many years later formed the basis of the philosophy of Epicurus (341–270 B.C.). The doctrines which Epicurus developed in his celebrated garden at Athens dealt largely with life and conduct, and were summed up in the inscription " Here pleasure is the highest good ". His natural philosophy, including that of Democritus, is expounded in the poem of Lucretius—" De Rerum Natura ".

First, it was stated that matter consists of atoms, which

by their combination form substances. The atoms themselves are eternal and unchanging.

Secondly, that motion is inherent in atoms.

Thirdly, that empty space exists, by which displacements of the atoms are possible.

It follows from these statements that the atoms are indivisible. They are too small to be perceived by the senses, but differ from each other in shape and size and *arrangement*.

If the atoms are in perpetual motion, why is the substance which they form in a state of rest? Lucretius in the poem very beautifully compares this motion to that of flocks on a distant hill; though the lambs gambol, and the flocks move on to the new pasture, all seem to be at rest, a white spot on the green.

This approximation to the truth is all the more marvellous when we consider that it was all arrived at deductively, and that not one single experimental fact could be brought forward to support such theory. Everyone knows to-day that the atoms are no longer in the realm of theory, but are actual things whose weight can be ascertained and whose perpetual motion confirmed.

Nevertheless, such surmises as to the constitution of matter were of little value. Natural science was not advanced by them, no new facts were brought to light by which a progressive science could be built up; everyone was content to theorize without facts.

It is difficult to estimate the contribution made by the genius of Socrates (470–399 B.C.) to the logical methods of philosophy at that time. His methods persisted in the school of his pupil, Plato; and again are to be seen employed by his pupil's pupil, Aristotle. Socrates apparently abandoned the study of natural philosophy, giving himself up to the study of humanity. He invented no new theory as to the composition of matter, or the

elements possessed two of the qualities warm, cold, dry, moist. The differences of material substances depended upon the degree of blending of these. In addition to the four elements Aristotle assumed a fifth—the ethereal essence. Probably these beliefs were borrowed from the ancient writings of India.

One may ask what was the contribution of Greece to the advancement of natural science. Her philosophers were prone to speculation, which they entered upon with greatest boldness; they did not realize that gaining knowledge of nature was a slow process to be executed systematically, and by testing each step. The Greeks would introduce into their philosophy abstract notions about which they would argue, without once putting these notions to a practical test. Their *direct* contribution to physical knowledge was insignificant.

On the other hand, the indirect contribution to the advancement of science was great. Men learnt to deduce correctly from incorrect starting-points. This was the work of the philosophers who founded schools of vigorous abstract thinking, where before no thought had existed. They taught how to state a general proposition, and to arrange the results of argument clearly. Without such mental training progress would have been greatly retarded.

CHAPTER II

THE ATOMIC THEORY

After the conquest of Spain in A.D. 711, the Arab conquerors carried Greek philosophy into the west of Europe. Arab scholars translated and expounded the beliefs of Aristotle and the Peripatetic school, and encouraged

complete submission to them. Other Greek systems were not entirely neglected, such as those of Democritus and Epicurus.

By the Arabs chemical knowledge was greatly increased—not as a science in itself, but as an instrument in alchemy. The doctrine of the transformation of one substance to another had been taught by Aristotle; the alchemists, ever faithful to his teaching, strove to bring this about. Geber added two more elements to the four —fire, air, water, earth. These were sulphur and mercury. The metals were regarded as compounds, and one metal could be changed into another by adding or withdrawing either sulphur or mercury. Paracelsus, who looked upon chemistry as the servant of medicine, taught that there was still another principle, first expounded by Basil Valentine—the element salt.

Very little advance in chemistry resulted from these views which were held for centuries, but many philosophers rebelled against them. Francis Bacon (1561–1626) opposed the beliefs and condemned the methods of the school of Aristotle. In the *Novum Organum* he accuses its followers of first deciding the question and then twisting experience or experiment to fit the decision. He advocates (1) the evidence of the senses as the starting-point of scientific knowledge, (2) the making of hypotheses, (3) verification of these and deduction from them.

The effect of Bacon's writings and of his new methods upon science was far-reaching; though the immediate results of his own research were quite insignificant. He disputed the possibility of changing metals into gold, and denied that matter was *infinitely* divisible, though he believed it to be made up of separate minute particles.

We need not consider the theories of Descartes, be-

yond noticing that they served to break down the authority of the doctrines of Aristotle.

But it was owing to the work of Robert Boyle (1627–1691) that the teaching of both Aristotle and Paracelsus about the elements was overthrown. He did not admit that matter is universally made up either of fire, air, water, and earth, or of sulphur, mercury, and salt, because it can be proved by experiment that these elements so called cannot always be obtained from all substances; moreover, there are many elementary substances besides these so-called elements or principles. Robert Boyle was the first to give that meaning to the term element which it holds to-day, namely, something which contains only *one* kind of matter. He seems to have been a believer in the existence of atoms, for an atomic view of matter was familiar to many men of science during that time. His chief experimental work was published under the title " Defence of the doctrine touching the spring and weight of the air ". Boyle was interested in the air-pump of Guericke—or in the " wind-pump " as he called it. He constructed a similar instrument with many improvements, and with this he compared the weight of the air with that of water, and carried out experiments upon a partial vacuum. He showed that a flame is extinguished in the latter, and that magnetic and electric actions can be carried on in the exhausted receiver, all of which actions can be shown experimentally (see end of chapter).

Whether or no these experiments were carried out by him in order to investigate if possible the atomic structure of matter, it is difficult to say. Assuming that matter is made up of minute particles, it would certainly occur to Boyle that these particles would be far more widely separated in a gas under reduced pressure than in the case of a liquid or a solid.

In the paper mentioned above he showed the connexion of the density of the air with its pressure. This law of Boyle's, that the volume of a gas is inversely proportional to its pressure, or that the density is directly proportional to the pressure, may be regarded as the foundation of molecular physics; it is necessary, therefore, to consider it in some detail.

In the year 1643 Torricelli, a pupil of Galileo, carried out experiments entrusted to him by his former master. Their object was to discover why an ordinary lift-pump could not raise water to the height of forty feet. Torricelli experimented with mercury, which is 13·65 times as heavy as water. He filled a tube of 33 in. length and closed at one end with mercury, and inverted it over mercury. He found that a column of this liquid about 30 in. in height remained standing in the tube. The support of such a column he correctly attributed to the pressure of the air. Between the top of the mercury column and of the closed tube there was what he assumed to be a vacuum; this space we now know to be filled with mercury vapour at a very low pressure. It was found that the height of this column varied from day to day, according to the quantity of water vapour in the air. Robert Boyle was the first to call it a barometer, and measured the pressure of the air in "head" of mercury, just as an engineer to-day might measure pressure in "head" of water, i.e. the height of a column of water that is producing a pressure. For example, let us suppose that the height of the water column is 1 m., the pressure in gm. wt. per square centimetre is 100, for the volume of water in a column 100 cm. long and 1 sq. cm. cross section is 100 c. c. If the column consisted of mercury instead of water, the pressure of a metre column per square centimetre would be 1365 gm. wt. Robert Boyle used a "head" of mercury in

order to submit a given volume of air to a series of different pressures. He used a column of mercury from 10 ft. to $1\frac{1}{4}$ in. in length, and found that the density of the air was proportional to the pressure under which it was measured, i.e. that the volume was inversely proportional to the pressure.

This law can be illustrated in the following manner. The apparatus (fig. 1) consists of two tubes of narrow bore (thermometer tubing can be used). The shorter tube is closed at the top and connected with the longer open tube by a piece of thick coated rubber tubing. Mercury is poured into the open tube, filling the rubber tube and the closed glass tube to a certain height. If the levels of mercury in each tube are the same, the air in the closed tube is at the pressure of the air; let us say at a pressure of h mm. of mercury. This means that the air at the time of the experiment supports a "head" of mercury h mm. The rubber tube is then compressed by means of the screws, the mercury rises in both tubes, but to a greater height in the open one. The volume of air in the closed tube has been reduced, and the pressure has increased to $h + h'$ mm., where h' is the difference in level between the two mercury columns as measured on the scale. Since the cross section of the closed tube is uniform the volume of air in it is proportional to the height of the air column. If now a graph is plotted of the pressures in millimetres of mercury, for various heights of the air column, and the various points are drawn, a curve is obtained such that the products of the ordinates

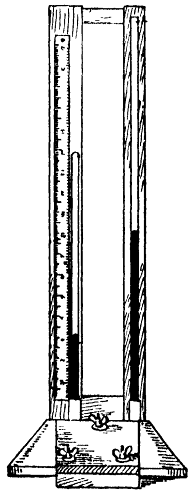
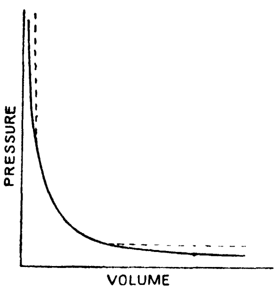


Fig. 1

are constant, i.e. $p \times h$ is constant (κ), so that $p = \frac{\kappa}{h}$. Such a curve is a rectangular hyperbola. The continuous line in the figure (fig. 2) illustrates it. For the range of pressure through which Boyle carried out his experiments the law is very nearly true. But what is to happen when the air is submitted to a pressure enormously great? Will the product of the pressure by the volume still be constant? Will 100 c. c. of air measured at the pres-



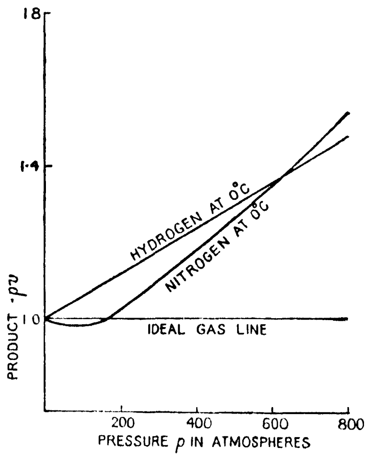


Fig. 2

sure of one atmosphere become 0·1 c. c. at 1000 atmospheres? If the gas were infinitely compressible this would be correct. Robert Boyle had no means of testing the truth of his law for really high pressures, but it was shown by Amagat that, above pressures of 4 atmospheres, the product pv is not constant, but steadily increases with the increase of pressure. If, as in fig. 2, pv is plotted against p, for hydrogen and nitrogen we note a steady slope upwards. If Boyle's law were true for all pressures we should obtain a straight line, horizontal and parallel to the axis of pressure. The facts become

intelligible if we suppose that a gas is made up of minute particles between which there are considerable empty spaces. Let us suppose that 1 per cent of the total volume constitutes the volume of the particles themselves; then the remaining 99 per cent consists of space. If the pressure is doubled, the 100 volumes of gas become 50, of which $\frac{99}{2} = 49{\cdot}5$ volumes are space, and 1 volume——assuming that the actual particles are incompressible—is that occupied by the material of the gas. So that the volume is 50·5 and not 50 as the law requires. Actually, the space occupied by the gas material is far less than 1 per cent, consequently the inaccuracy of the law is apparent only at high pressures. Thus it was that Robert Boyle had in his hands an important piece of evidence of the molecular structure of matter. It is to be noted that the term molecule was not used at that time, though atoms and particles were spoken of.

About this time Sir Isaac Newton (1642–1727) turned his attention to the many speculations about atoms. The reason why the great mathematician, who was not given to speculation, should take up such a subject was that he recognized the necessity for the existence of a vacuum in interstellar space. His calculations required that the earth in its motion round the sun should experience no resistance. If a vacuum exists in the space between the stars, why not in material substances upon the earth? Given the existence of a vacuum, atoms must of necessity follow. In the *Opticks* Newton speaks of these atoms: "These primitive particles, being solids, are incomparably harder than any porous bodies compounded of them, even so very hard as never to *wear or break in pieces*. . . . Should they wear away, or break in pieces, the nature of things depending on them would be changed."

It is astonishing to note how true these observations

are in the light of our present knowledge. What "wearing away" of the particles there is is confined to the radio-active elements as far as we can tell; it cannot be hurried or retarded by any means at our disposal, nor can it be brought about except by using the energy of radio-active change.

The authority which the great Newton lent to the atomic view of matter had much influence upon its establishment.

We must now pass to another line of approach to the problem of the structure of matter—the nature of chemical change. Owing to the persistent fallacies of the Peripatetic school it was believed that since matter consists of mixtures in different proportions of fire, air, water, and earth, it is easy to change from one kind of material to the other; and that such a change is quite a haphazard proceeding. It was believed that during the burning of a substance the fire principle—phlogiston—escaped; that a metal consisted of a mixture of what we now know to be the metal, and phlogiston; and that, after heating, the phlogiston escaped, leaving the calx or oxide of the metal behind. Lavoisier showed the error of such a view, and that combustion was chemical combination *with an increase of weight*, the burning material and the oxygen of the air forming together a new substance.

The question which next arose concerned the composition of these new compounds. When iron, for example, combines with the oxygen of the air, does it form a compound of constant composition? Berthollet (1748–1822) affirmed that chemical compounds are variable in composition; that two elements could combine in ratios which vary continuously. If sodium hydroxide in solution is added in small but vároying quantities to a copper sulphate solution it is found that in each case a precipitate blue in colour and gelatinous is thrown down. The

constitution of these precipitates is not the same. Berthollet argued therefore that specimens of copper hydrate of varying composition had been produced. We now know that the precipitates consisted of *mixtures* of copper hydrate with varying amounts of the copper sulphate precipitated with them. Proust (1755–1826) questioned the results obtained by Berthollet, and many papers were written by both these chemists in their dispute. However, Proust showed that compounds produced under absolutely different conditions had the same chemical constitution. We may, for example, obtain the black oxide of copper either by heating the carbonate of the metal, or by oxidizing the latter with strong nitric acid; the substances formed will have exactly the same composition in each case.

By his investigations Proust established one of the fundamental principles of chemistry. It may be thus stated. The ratio of the constituents of a chemical compound is fixed and invariable. From 88 parts of sulphide of iron can be obtained 56 parts of iron and 32 of sulphur; no more and no less.

Is it possible for two elements to combine in more than one proportion, producing two different compounds? Proust was the first to show that this could be done. However, he failed to see what John Dalton perceived: that if an element A combines with another B in more than one proportion the two compounds produced contain quantities of B which bear a simple ratio to each other. Dalton showed that a given quantity of oxygen would combine with a certain quantity of nitric oxide, or with *twice* that amount.

More exact experiments upon this question were carried out by Berzelius, who showed that 100 parts of lead would combine with either 7·8 parts of oxygen, or with 15·6 parts, twice as much; 100 parts of copper

combine with either 12·3 parts of oxygen, or with 25 parts, very nearly twice as much. It seems strange that Proust, an accurate experimenter, should have missed this simple relationship, but then he was not given to the making of hypotheses, whilst Dalton was, above all, a theorist. There seems to be little doubt that the evidence brought forward by the latter was the result of experiments carried out to support the theory; that the hypothesis *preceded* the experimental work. Dalton, in the first place, was a meteorologist, and had kept weather records for several years. He could not understand why the composition of the air should be uniform throughout; why should there be a perfect mixture of the gases of the atmosphere?

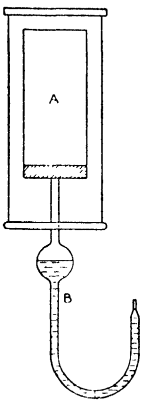
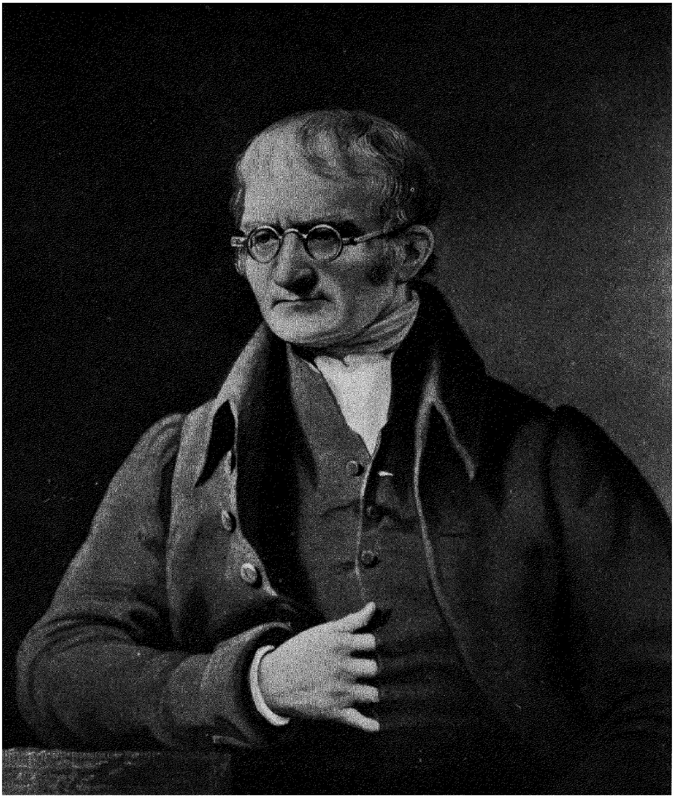


Fig. 3

If we fill a gas-jar with hydrogen or coal-gas—both of these gases lighter than air—and support it on a stand, mouth downwards, we shall find that, in a short time, all the gas has escaped and the jar is full of air. The gas, though lighter than air, must have moved downwards to get out of the jar; it has diffused. It was just this power of diffusion that Dalton found difficult to understand.

Here is another experiment to illustrate diffusion (fig. 3). The gas-jar filled with hydrogen is placed over the vessel A, a porcelain battery cell, fitted with a rubber stopper and glass tube B, with a bulb containing water, and terminating in a jet. The hydrogen in the jar diffuses through the pores of A more rapidly than the air can pass out, consequently the volume of gas in A is increased, and the water is forced out of the jet in a spray.



JOHN DALTON, 1766–1844

After the painting by James Lonsdale

Facing page 20

What must be the nature of the structure of the gases to account for these facts?

Newton had shown in the *Principia* that an elastic fluid, such as a gas, consisted of minute particles or atoms which repel each other, striving constantly to occupy a greater space. Dalton, to use his own words, "set to work to combine these atoms on paper". Here are his *deductions*: In the first place he denied that matter was infinitely divisible, but assumed that there was a limit to the subdivision—the atom. He rejected the idea of one kind of matter endowed with various properties, believing in the existence of a considerable number of "elements"—substances containing uniformly one kind of matter and differing from each other. He is very cautious over accepting a substance as an element without rigid test. In his Manuscript Notes he says we may not know what elements are absolutely decomposable—"because we do not apply the proper means for their reduction". At the same time he speaks of elements which cannot be changed into one another by "any power under our control". An element represented to Dalton what it does at the present time—the limit of chemical analysis.

Here is the difference between Dalton's theory and the speculations of the Greeks. He affirmed that the atoms, though all alike for the same element, differed in the case of each element in mass and volume. That is to say that the particles arrived at by the greatest possible subdivision depended for their dimensions upon the nature of the substance divided. If one element combined with another the process took place *atom for atom*. One atom of one element would combine with one or more atoms of another element, but there would be always a *whole number* of atoms taking part in the process. Granting the atomic theory to be true, how does it interpret the

law of constant composition? Let us consider a compound consisting of two elements A and B. Let the weight of an atom of A be a, and that of an atom of B be b. Further, let us suppose that X atoms of A and Y atoms of B combine to make what Dalton called an "atom" of the compound. Then the weight of A combining with B will be Xa; and the weight of B will be Yb. In the case of mercuric oxide it is found that 200 gm. of mercury combine with 16 gm. of oxygen. Then the proportion by weight in which the atoms combine is

$$\frac{Xa}{Yb} = \frac{200}{16},$$

and this proportion is fixed and invariable. We do not know what numbers X and Y or a and b represent; the data are insufficient, as they were in Dalton's time.

The law of multiple proportions must follow as a consequence of the theory. Suppose we find that carbon forms two compounds with oxygen; in one 12 parts of carbon combine with 16 of oxygen, in the other 12 parts combine with 32. In the first case $Xa : Yb :: 12 : 16$; in the second $Xa : Y'b :: 12 : 32$. Therefore

$$\frac{Yb}{Y'b} = \frac{16}{32} = \frac{1}{2}.$$

The amount of oxygen combining with Xa has doubled; this must be the case as *whole numbers* of atoms only can combine. The ratio might be 1 : 2 or 1 : 3 or any small whole number.

These facts that Dalton foresaw as a consequence of the theory were actually shown experimentally by Berzelius.

How does the theory account for the facts revealed in the diffusion experiment mentioned above? If the gas

hydrogen consists of minute particles (called atoms by Dalton) which are constantly repelling each other, such particles will intermingle with the air after passing through the pores of the porcelain jar. The mass of the hydrogen particles is less than that of the air particles, so that the rate of diffusion is greater.

Experiments

1. Invert the open end of a barometer tube filled with mercury, over mercury, and note the difference in level of the liquid inside the tube and outside. Place the tube in a tall glass tube and upon the plate of an air-pump (see fig. 4), and gradually exhaust the air, showing that the level of the mercury in the tube sinks nearly to the level outside.

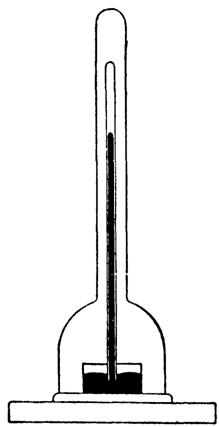


Fig. 4

2. Carry out an experiment to show the relation between the pressure and volume of a gas at constant temperature.

3. Show by the heating of magnesium ribbon in a weighed, closed crucible, that there is a gain in weight. By cautiously lifting the lid of the crucible, show that the metal burns (with what the alchemists believed to be an escape of phlogiston). The white ash left is heavier than the original metal.

4. Show by an experiment that when phosphorus burns something is taken from the air.

5. Determine the loss per cent incurred when copper carbonate is heated; show that this loss is a constant.

6. To show that copper oxide is of constant composition, weigh out 1 gm. of copper turnings, dissolve in nitric acid (1 of water to 1 of acid), and make up the volume of the solution to 20 c. c. To 10 c. c. of this solution add sodium carbonate solution to precipitate completely the copper as carbonate; wash, dry, and heat the precipitate in a crucible,

obtaining copper oxide. Evaporate remaining 10 c. c. of copper nitrate solution to dryness, and heat strongly in a weighed dish. Is the weight of the black residue obtained by each method the same?

7. To a tube containing 18 c. c. of nitric oxide standing over water add 10 c. c. of oxygen gas by means of a Hempel burette. Repeat the experiment, using 36 c. c. of nitric oxide; what changes take place?

8. Carry out experiments on diffusion mentioned above.

9. Find the percentage of lead in the two oxides, litharge and lead peroxide. Weigh out 2 gm. of each oxide in a porcelain boat; heat the boats in a hard glass tube through which a current of coal gas is passing. Note what takes place during the heating. Pure lead is left.

The loss of weight gives the weight of oxygen present in the original oxide. Hence determine what weight of oxygen was combined originally with 207 gm. of lead in each case.

N.B.—It is necessary to be quite clear as to what question you are asking in each experiment.

CHAPTER III

THE MOLECULE

We have seen how Dalton's Atomic Theory was able to account for the constant composition of chemical compounds and for the law of multiple proportions. In some respects, however, the original theory did not cover the known facts and those which were discovered a few years later. Dalton insisted on the existence of the "atoms" of a compound; he called the ultimate particle of carbonic acid, for example, a compound atom. This seems to us illogical, since the term atom means an indivisible particle, and carbon dioxide particles can be decomposed into their elements.

In 1805 Gay-Lussac and Humboldt published the results of experiments they had carried out on the "Ratio

of the Constituents of the Atmosphere". In their experiments hydrogen had been used to remove the oxygen present by explosion with it. It was found that almost exactly two volumes of hydrogen were required to combine with one volume of oxygen; the volume of water formed being insignificant. Gay-Lussac investigated the proportions by volume in which other gases combined. In every case he found that the ratio in which they combined could be expressed by small whole numbers. Here are a few examples.

(*a*) One volume of hydrogen combines with one of chlorine forming two volumes of hydrogen chloride.

(*b*) One volume of nitrogen with three volumes of hydrogen forming two volumes of ammonia.

(*c*) One volume of oxygen with two of hydrogen forming two volumes of steam.

(*d*) Two volumes of nitrogen with one of oxygen forming two volumes of nitrous oxide.

The ratios in the four cases are:

(*a*) 1 : 1 : 2
(*b*) 1 : 3 : 2
(*c*) 1 : 2 : 2
(*d*) 2 : 1 : 2

The outstanding feature of the atomic theory was that from the proportions in which various elements combined the *relative* weights of the atoms could be inferred. It was the constant endeavour of chemists at that time to find those *combining weights* of the atoms. Gay-Lussac showed in his work that not only did the volumes in which gases combined bear a simple relation to each other (as above), but also the weights of these volumes were simply related to the combining weights.

You will by this time have gained the impression that

the scientist goes a-hunting for simple facts less than for ratios and proportions, his proper quarry. The isolated discoveries, e.g. of new compounds, serve as interesting snap-shots by the way, but the relationships between one series of natural phenomena and another are the big game.

Now if the connexion between the volume of the gases and their combining weights holds, Gay-Lussac reasoned that his examples must be cases of combination, atom for atom, according to Dalton's theory. If this is so one atom of hydrogen combines with one atom of chlorine to form two compound atoms of hydrogen chloride. It must follow, therefore, that half an atom of hydrogen combines with half an atom of chlorine to form one atom of hydrogen chloride. Here is a complete *reductio ad absurdum*, since we know that half an atom of an element cannot exist.

Either the atomic hypothesis as Dalton expressed it was untrustworthy, or else Gay-Lussac's facts were at fault. Dalton preferred to believe the latter—not so much from his objection to having his own theory upset as from genuine doubt as to the correctness of the volume experiments. The accuracy of modern work was unknown at that time, and we find Dalton making the following statement: "According to Davy 100 measures of oxygen require 192 of hydrogen, but *from the most attentive observations of my own* 185 are sufficient". Both results are wrong; 100 of oxygen require 200 of hydrogen. To Dalton the difference of 4 per cent between his own and Davy's result did not appear to be serious.

However, it became obvious that Gay-Lussac's facts were indisputable. We can test one of his statements as follows.

In (*d*), p. 25, two volumes of nitrogen were said to combine with one of oxygen to form two of nitrous oxide.

The ratio of the volume of nitrogen to the volume of nitrous oxide is 1 : 1. So that if we take away the oxygen from a litre of nitrous oxide we shall have a litre of nitrogen left, and there will be no alteration in the original volume. A flask A is fitted with a rubber stopper, through which passes a metal spoon D, and a wire terminating in a platinum spiral C, and touching D (fig. 5).

The side tube terminates in a U tube, B, which contains mercury, the levels adjusted to be the same when the flask is closed. A is filled with nitrous oxide, and a piece of phosphorus is placed in D; the stopper is then fitted into the neck of the flask. The platinum spiral is heated by means of a battery to ignite the phosphorus, which combines with the oxygen of the nitrous oxide.

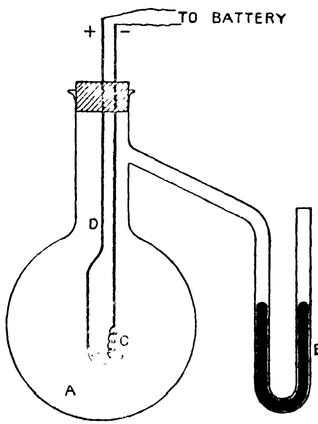


Fig. 5

When the flask has cooled to room temperature it is found that the levels of mercury are unaltered. The gas left in A is nitrogen and will not support combustion. Hence the volume of nitrogen left equals the original volume of the nitrous oxide.

It was Avogadro who showed how Dalton's hypotheses must be modified to cover the facts mentioned above. In the first place the constitution of matter was not so simple as he (Dalton) imagined. There were two kinds of ultimate particle, one constituting a group of atoms and capable of existing alone; the other was the atom, the smallest particle of an element which could enter into

combination. That particle which could exist in the free state Avogadro called the *molecule*. According to his view molecules consisted of groups of atoms—frequently two atoms, sometimes four or more. When combination took place these molecules first separated into their elementary atoms; these latter regrouped themselves forming molecules of the compound.

For example: one molecule of hydrogen containing two atoms of the element, on reacting with one molecule of chlorine, separates into two atoms of hydrogen; the chlorine molecule separates also into two atoms. One atom of hydrogen then combines with one atom of chlorine to form a molecule of hydrochloric acid. Hence:

$$H_2 + Cl_2 = H \cdot H + Cl \cdot Cl = HCl + HCl.$$

Two molecules of hydrogen chloride are thus formed from one molecule of hydrogen and one of chlorine. The two molecules of hydrogen chloride *inhabit the same space* as the original two molecules of hydrogen and chlorine.

In the case of the formation of water: Two molecules, each consisting of two atoms of hydrogen, combine with one molecule of oxygen containing two atoms:

$$H_2 + H_2 + O_2 = H \cdot H + H \cdot H + O \cdot O = HOH + HOH.$$

The two molecules of water formed contain *three* atoms each, and inhabit *two-thirds* of the volume of the original gases.

In order to get a clearer idea of the nature of a gas we must refer back to Boyle's law. We may state it in the following manner: The density of a gas, i.e. the degree of concentration of its particles, is directly proportional to the pressure to which it is submitted, and this is true (the allowances mentioned above being made) for all gases.

Moreover, the behaviour of a gas with rise of temperature had been investigated by Charles, and it had been shown by Gay-Lussac that a given volume of gas at 0° C. expanded $\frac{1}{273}$ of that volume at 0° for each degree rise in temperature. If we start with 1 litre of gas at 0° C. we shall have 2 litres at 273° C., provided the pressure remains constant. Again, this was shown to be (approximately) the case for all the gases investigated.

If a gas consists of molecules with spaces between them, how can we account for the above facts?

Ampère, in his paper on Avogadro's law, suggests that "the particles of all gases are equidistant from each other".

If all gases obey Boyle's law, and expand uniformly by the same amount per unit rise of temperature, the inference is that, under the same conditions of temperature and pressure, equal volumes of gases must contain the same number of molecules—obviously a truly enormous number, but in every case the same. This was Avogadro's hypothesis; using it, we can state the volume changes in the formation of steam from its elements as follows:

$$\left.\begin{array}{l}\text{One volume of oxygen}\\ \quad\text{containing X mole-}\\ \quad\text{cules}\end{array}\right\}\text{combines with}\left\{\begin{array}{l}\text{Two volumes of hy-}\\ \quad\text{drogen, each con-}\\ \quad\text{taining X molecules,}\end{array}\right.$$

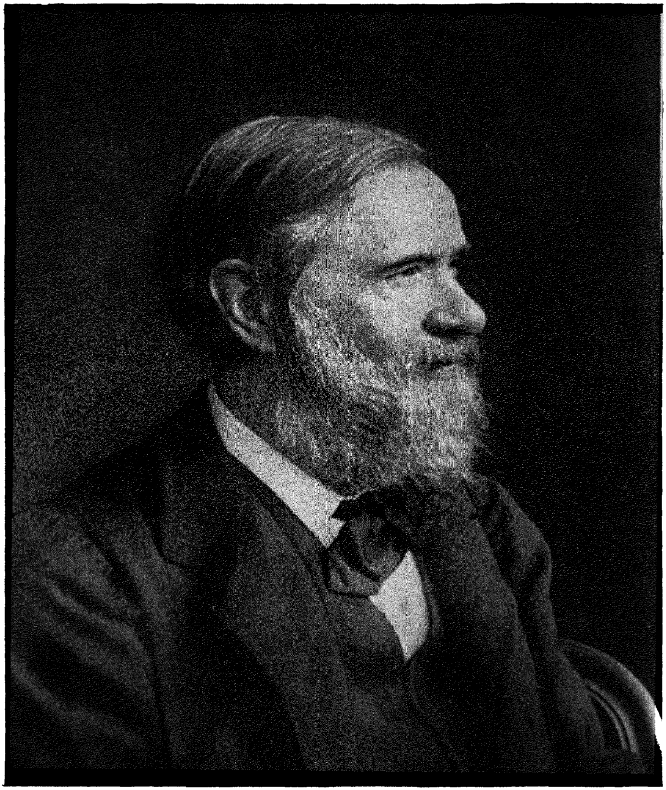
$$\text{and produces}\left\{\begin{array}{l}\text{Two volumes of steam,}\\ \quad\text{each containing X}\\ \quad\text{molecules;}\end{array}\right.$$

where X is a very large number, approximately 62×10^{22} for a volume of 22·4 litres (see p. 38).

Here was the reason for Gay-Lussac's law of volumes; whilst Dalton's atomic theory was greatly strengthened. However, the hypothesis was neglected; partly because the number of gaseous substances known at that time

was small, and the time of most chemists was taken up in finding relative atomic weights. In the finding of these weights there was great confusion, until Laurent defined the atom as the smallest quantity of an element that exists in a combined state; the molecule as the smallest particle existing alone. At length Cannizzaro showed how the molecular and atomic weights could be determined, if Avogadro's hypothesis were granted. Thus he established these quantities on their modern basis. Briefly, the argument is this: A given volume of the vapour of a substance at known temperature and pressure weighs x gm., whilst an equal volume of hydrogen weighs y gm. under the same conditions. Therefore the vapour density of the substance relative to hydrogen $= \frac{x}{y}$. Now equal volumes (of vapour and of hydrogen) contain the same number of molecules. Therefore if the molecule of hydrogen weighs 1, the weight of a molecule of the vapour $= \frac{x}{y}$. But a molecule of hydrogen consists of two atoms and weighs 2. Therefore the molecular weight of the substance $= \frac{2x}{y}$, (or one molecule is $\frac{x}{y}$ times the weight of one molecule of hydrogen).

Further, if we know the composition per cent of a compound and also its molecular weight, we can find how much by weight of a certain element is found in that molecular weight. By treating several compounds containing that element in the same manner we can find the *smallest* weight ever found in the molecular weight relative to oxygen as 16, i.e. the atomic weight. An example will make this clear. Seventy-five per cent of carbon is found to be in a compound whose molecular weight is 16; in 16 parts of the compound there are 12 of



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CANNIZZARO

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carbon (75 per cent of 16). Is 12 the *smallest* weight ever found in any molecular weight? By testing hundreds of cases it has been shown that never less than 12 parts of carbon are found in a molecular weight. Therefore 12 must be the atomic weight of carbon, unless a compound is discovered which contains less than 12 parts of carbon per molecular weight.

It will be seen from what has been said that the existence of atoms and molecules "accepted as a hypothesis" can explain the physical and chemical behaviour of elements and compounds; or, given the laws of chemical combination and those of Boyle and Charles, we, by a process of deductive reasoning, arrive at the conclusion that atoms and molecules do exist. We have no *direct evidence* for their existence. That the molecules of a gas, according to our hypothesis, must be in rapid motion, must follow from the fact that gases will diffuse and mix with each other irrespective of their weight.

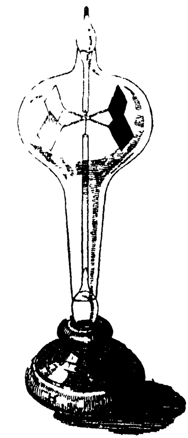


Fig. 6.—Crookes' Radiometer

But before considering the motion of the gas particles—what is the evidence for the presence of these particles?

In the first place there is the action going on in the radiometer (fig. 6). This instrument consists of a glass bulb, partially exhausted of air, in which revolves on a pivot a small paddle wheel with mica vanes, the latter being blackened on one side and silvered on the other. When the bulb is exposed to a source of radiant heat, the paddle revolves, the blackened sides receding from the source. This is explained as due to the unequal

bombardment by the moving molecules. The blackened sides are better absorbers of heat than the silvered sides, therefore the molecules near the blackened surface possess greater kinetic energy and bombard the vane more vigorously on that surface, producing a rotation with the black surface receding. However, if the bulb is not exhausted at all, there is no rotation. Further, if the pressure within the bulb is not low enough the rotation takes place with the black surfaces *advancing* towards the source of heat. On the whole, we cannot regard the evidence of the radiometer as conclusive.

In 1827 the botanist, Robert Brown, discovered what is now known as the Brownian movement. When a liquid containing fine particles in suspension is examined by a microscope of fairly high power it is found that the minute particles are in a state of constant movement which is absolutely irregular. Apparently it is not affected by small variations in temperature, and it is continuous so long as the particles remain suspended in the liquid. It is found that the average length of the path through which these tiny particles dart is inversely proportional to their mass.

The reason for the motion remained a mystery for many years, but in 1876 it was suggested by Ramsay that the movement of these small grains was due to the impacts of the molecules of the liquid upon them; that we have an epitome of the movements of the darting molecules in the motion of the particle under inspection.

The Brownian movement may be seen through the microscope in a suspension of gamboge in water. A piece of gamboge, such as that used by architects in drawing plans, is rubbed under water. A yellow, cloudy liquid is obtained; a few drops of this are placed on a slide and carefully covered with a cover slip. If a $\frac{1}{4}$-in. objective, or, better, a $\frac{1}{6}$-in., is used, the particles suspended

in the liquid are seen moving with a zig-zag motion across the field. This motion is quite distinct from that due to convection currents in which streams of particles are carried in one direction. It is also *continuous*, remaining undiminished for years, provided the liquid is protected from evaporation. Have we then arrived at a perpetual motion? You will see, when considering the kinetic theory of gases, that such a motion is by no means impossible in *the case of molecules*. We know that for objects of such magnitude as are perceptible to our sight, and which are measured on a scale of centimetres and millimetres, perpetual motion is impossible, as it involves an unlimited supply of energy. But suppose that the particles are of molecular size, the kinetic energy of these molecules is supplied by and is a measure of the heat which they contain. We can imagine a state in which the temperature is constant; every gain of velocity of a molecule is accompanied by cooling, and every diminution of velocity by local heating, but the net result is a constant temperature with a perpetual motion.

Is it not possible that the tiny particles of gamboge are subjected to molecular bombardment? If these particles are very small, though many times the size of the molecules, they will be submitted to unequal pressures, like a large vessel tossed by waves, and will be driven in random directions.

There is a great deal of evidence to show that the Brownian movement is caused by the bombardment of molecules. For example, a suspension of arsenic sulphide, whose density is measured either by a hydrometer or by actual weighing of a given volume of the suspension, shows the same result. In the case of the hydrometer, a glass cylindrical vessel is floated in the suspension, the greater the density of the latter the higher will the hydrometer stem be raised in the liquid. The upward

pressure A (fig. 7) of the liquid is equal to the downward force B the weight of the hydrometer. This upward pressure in liquids generally is really the net result of molecular bombardments upon the instrument.

If the particles of the suspension can so bombard the hydrometer and raise it to a point C, so that the density it indicates is the same as that found by weighing, it follows that the particles are behaving like molecules.

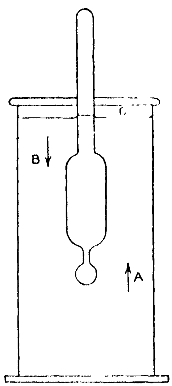


Fig. 7

That the true cause of Brownian movement was molecular was demonstrated in a striking manner by Jean Perrin. If gases consist of molecules, these latter must obey Boyle's law; the extent to which they are crowded together will depend upon the pressure of the gas. Since the concentration of the gas is directly proportional to the pressure, the number of molecules per unit volume is proportional to the pressure. The air is more rarified on mountain tops than at sea-level. If we ascend to a height of 5 Km. the pressure of the air is reduced to one-half; consequently its concentration is also reduced to one-half, and also the number of molecules per unit volume of air. The height to which we must ascend in a column of any gas in order that the half-concentration point may be reached depends upon the density of the gas, it is inversely proportional to the density. In hydrogen a height of approximately 80 miles is required.

The question to be decided in Perrin's investigation was: Do emulsions, such as arsenic sulphide or a suspension of gamboge in water, obey the gas laws, e.g. Boyle's law?

If we have a column of water containing this suspension,

will the number of particles per unit volume become halved at a certain height, become one-quarter at another height, one-eighth at another, these heights being proportional to such heights as are obtained in gases?

Consider the forces acting upon these gamboge particles: there is the action due to gravity pulling the particles downward, and, acting in opposition to this, the Brownian movement which tends to scatter them. When equilibrium is established—which according to the experiments is soon brought about—these effects of gravity and the Brownian movement are equal and opposite. If we assume the gamboge particles behave exactly as enormous molecules, we can deduce how many times greater the effective weight of one of these is than a molecule of a gas. If the height at which half-concentration is obtained in the gamboge suspension is $\frac{1}{20}$ of a millimetre, and the height in oxygen is 5 Km., then

$$\frac{\text{weight of a gamboge particle}}{\text{weight of a molecule}} = \frac{5 \times 1000 \times 1000}{\frac{1}{20}} = 10^8.$$

So much for the deduction. The experiments are full of difficulties which were overcome in a brilliant manner by Perrin. In the first place it was necessary that the gamboge particles should be uniform in size, otherwise their behaviour could not be analogous to that of molecules.

This was attained by submitting the suspension to centrifugal force. By whirling round the suspension the heavier particles would sort themselves out, and settle first of all, since the friction upon their surfaces would be less, relatively to their mass, than with the smaller particles.

Speeds up to 2500 r.p.m. were employed, and, by repeated centrifuging, particles of the same diameter were obtained.

The volume of the grains was determined by several methods; by measurement of their diameter, by direct weighing. In the first case a drop of the emulsion was evaporated, and it was found that the grains were deposited in chains, having run together during evaporation. By counting the number in a chain, and by finding the length of the chain, either by direct measurement in the microscope or by means of a photograph of known magnification, the mean radius and hence the volume of a grain could be found.

In the method of weighing: the concentration is known of the particles in a droplet withdrawn, by actual counting of the grains in a given small volume. The weight of the suspended material in the droplet is found by weighing the residue after evaporation. The mass of a grain can be found, and if the density of the material is known (weight per unit volume) the volume of each grain can be found.

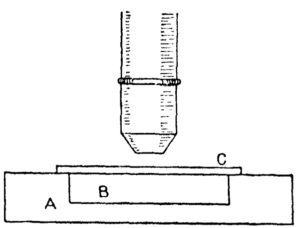


Fig. 8

It was then necessary to find how the concentration of the grains varied at different heights. A slide A (fig. 8), with a shallow depression B which contains the suspension of the assorted grains of gamboge, is covered with the glass slip C and placed under the microscope objective. The latter is focused on a layer of the liquid at a certain depth. An instantaneous photograph is taken and the number of grains counted from it. The miscroscope objective is raised through $\frac{1}{20}$ mm. and another photograph is obtained from which a second count is made.

By *repeated* countings it was found that the countings at various levels gave numbers which were in geometrical

progression, the numbers decreasing with increase of height. Here are some of the figures obtained.

Height from Bottom of Slide.	Relative Numbers Obtained.	Numbers decreasing in Geometrical Progression.
5μ	100	100
35μ	47	48
65μ	22·6	23
95μ	12	11·1

$\mu = 10^{-3}$ millimetres.

Now this decrease of concentration in geometrical progression is precisely what happens in the case of a gas.

Moreover, by finding in a series of suspensions in which the grains varied in mass the heights at which the concentration was reduced to one-half, it was shown that these heights were inversely proportional to the relative weights of the particles. Thus the deductions spoken of above were all shown to be correct. The behaviour of particles in Brownian movement is the same as that of molecules in liquids and gases.

But by far the most useful portion of Perrin's investigation was the estimation of what is known as the Avogadro constant. If all gases at the same temperature and pressure contain the same number of molecules per unit volume, it follows that a molecule of any gas at a given temperature and pressure must inhabit a definite volume which is independent of the nature of the gas. Therefore the molecular weight in grammes of a gas at normal temperature and pressure must occupy the same volume, no matter what the gas is. This volume is 22,400 c.c. The number of molecules present in this

volume must be (at normal temperature and pressure) *a constant for all gases* and is called the Avogadro constant.

From Perrin's results we have a means of determining this enormous number. Let us suppose that the gamboge grains are enormous molecules 10^8 times the weight of an oxygen molecule. Now 32 gm. of oxygen is the molecular weight of the gas in grammes, therefore 32×10^8 gm. of the gamboge material is its hypothetical molecular weight. If by careful experiment the individual weight of the grains is found, the number of grains (i.e. molecules) in 32×10^8 gm. can be found, which is the Avogadro constant.

As a result of many careful experiments Perrin's final value for the constant was $68{\cdot}2 \times 10^{22}$. That the Brownian movement was really caused by molecular bombardment he considered to be proved by the above experiments. But the most conclusive proof of this fact came from the close agreement of the Avogadro number as obtained by Perrin with that obtained by the kinetic theory of gases. It is easy to see that if a certain value is obtained by two absolutely independent methods, the trustworthiness of that value is enormously strengthened—so much so that the assumptions made in the employment of the methods are lifted into the realm of certainty. Other methods for finding the constant have given results which confirm Perrin's work. The most trustworthy value for Avogadro's constant is that obtained by the study of a spray of electrified oil drops by the American physicist Millikan; it is $60{\cdot}62 \times 10^{22}$. Knowing this number we can find the mass of a molecule or of an atom of oxygen. For 32 gm. of oxygen contain $0{\cdot}6062 \times 10^{24}$ molecules; therefore the mass of one molecule $= 32 \times \frac{1}{0{\cdot}6062 \times 10^{24}}$, i.e. $32 \times 1{\cdot}65 \times 10^{-24}$ gm. ($1{\cdot}65 \times 10^{-24}$ is the reciprocal of the Avogadro constant).

Since a molecule of oxygen contains two atoms the mass of an atom of oxygen is $16 \times 1{\cdot}65 \times 10^{-24}$ gm.

Nothing has been said about the size or the shape of the molecules so far. We have discussed their mass and the number of them in a given weight—the molecular weight in grammes—but the shape of the molecules of various materials is still a matter for investigation.

Lord Rayleigh showed that in order to lower the surface tension of water (i.e. the resistance of the surface of the water to being broken) by pouring oil upon it, it was necessary to have a film of oil one molecule thick. The smallest thickness of such a film to produce a measurable effect on the surface tension was found to be 10^{-7} cm. If we know the weight of the oil used, and the area of the film when such a layer of oil is used, we can compute the area of the molecular weight in grammes when spread out in a film. This area contains the Avogadro constant, i.e. $0{\cdot}6062 \times 10^{24}$ molecules, its thickness being that of a molecule. Hence it was shown that the dimensions of the molecule are very different in different directions. For example, the width of a stearic acid molecule is $4{\cdot}7 \times 10^{-8}$ cm., whilst its length is 25×10^{-8} cm.

We must not forget, however, that the valuable deductions with regard to the nature of gases were obtained from the Kinetic Hypothesis of Daniel Bernoulli (1738), in which he assumed that the particles (and the molecules) were spherical, absolutely elastic, and so far removed from each other that they exerted no attraction. He assumed further that the particles were in a state of unceasing motion—in straight lines until they collided with each other or the walls of the vessel, when the direction of their velocity was changed. Since the particles are perfectly elastic the velocity is not abated by their collision, neither is it possible, owing to their smooth surface, to put any " side " on these minute billiard balls.

Bernoulli by this kinetic hypothesis accounted for the fact of Boyle's law that the pressure of a gas multiplied by its volume was a constant for a given temperature.

When does an hypothesis take rank as a theory? When it is capable by its application of grouping together facts and showing the relation between them; when it can still be used for explaining the newly discovered; when by its use we can foretell phenomena subsequently discovered.

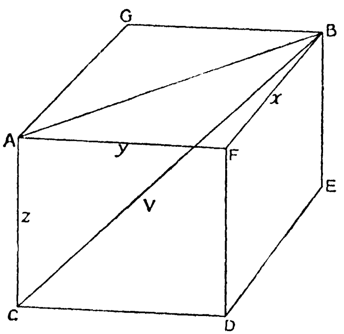


Fig. 9

All this the kinetic theory was able to do, as developed by Clausius. It is true that the particles or molecules are not round, hard spheres, neither do actual collisions take place. Nevertheless, by making the above assumptions certain well-known facts emerge.

In the first place let us consider the velocity of the flying molecules of a gas, contained in a cube of 1 cm. edge. We can resolve the motions which take place in all directions into three directions at right angles to each other. Let x, y, z be the component velocities (fig. 9). Then

$$y^2 + x^2 = AB^2, \text{ and } AB^2 + z^2 = CB^2 = V^2.$$

Now the number of molecules is very large, consequently the number of impacts is very large. The distance through which a molecule can travel without a collision is very small (i.e. the *mean free path* is small). Consequently the velocity of the individual molecules will not differ greatly from the average velocity. Since there is no tendency for molecules to accumulate at any particular

place in the cube, we may suppose that the velocities x, y, z are equal.

$$\therefore V^2 = x^2 + y^2 + z^2; \text{ and } x^2 = y^2 = z^2 = \frac{V^2}{3}.$$

Let the mass of the molecule in grammes be represented by m. Consider a molecule travelling in a line at right angles to the side FDEB of the box with a velocity y cm. per second. Its momentum will be my, and at each impact with a wall this changes from my to $-my$, i.e. $2my$. The time taken to travel from one wall to the other is $\frac{1}{y}$. There are y impacts with the wall per second, and change of momentum per second is $2my^2$. Half of the collisions take place at one wall and half at the other. Therefore the force exerted on one wall is my^2 dynes. But $y^2 = \frac{V^2}{3}$.

Therefore pressure due to one molecule:

$$p = \frac{mV^2}{3}.$$

If the cube contains n molecules, the pressure in dynes per square centimetre:

$$p = \frac{mnV^2}{3}.$$

If the volume of the cube were v c. c., the total number of molecules would be nv (since there are n molecules per cubic centimetre); then

$$pv = \tfrac{1}{3}nmV^2v.$$

The product of the volume and the pressure of a gas depends on V^2, since nmv, the total mass, is constant. For a temperature which does not alter this value V^2

remains constant. Hence pv is *constant*—which is Boyle's law.

Again, if we consider two litre flasks, each containing different gases, X and Y, at the same temperature and pressure, we may assume that the average kinetic energy of the molecules of each gas is the same. In the equation

$$pv = \tfrac{1}{3}nmV^2v,$$

if v is constant p varies as V^2. It is known that for a constant volume the pressure of a gas is proportional to the absolute temperature T. Therefore $T \propto V^2$, and, if T is reduced to zero, V^2 becomes zero also.

The kinetic energy of a molecule $= \tfrac{1}{2}mV^2$; but $V^2 \propto T$, and m is constant, therefore for gases at the same temperature the average kinetic energy of the molecules is the same.

So that for the two gases X and Y mentioned above we may write

$$\tfrac{1}{2}m_XV_X^2 = \tfrac{1}{2}m_YV_Y^2.$$

Now pv for both gases is the same;

$$\therefore\ \tfrac{1}{3}n_Xm_XV_X^2v = \tfrac{1}{3}n_Ym_YV_Y^2v.$$

Therefore $n_X = n_Y$. The number of molecules in each litre flask is the same—which is Avogadro's hypothesis.

We see, then, that long before the Brownian movement had received a satisfactory explanation, men had learnt to think of the molecules, submitting them in imagination to certain conditions. In this manner the behaviour of gases was deduced, the deductions being fully justified by actual experiment. The visible evidence of the ceaseless movement of the molecules was a startling confirmation of the kinetic theory. The glass of water which looks so still is really the centre of intense

activity, of molecules darting hither and thither and colliding many millions of times per second, their velocity being equal to that of a rifle bullet. The pressure exercised by a gas upon the sides of the vessel containing it, is really the sum of the millions of impacts of its molecules, just as the continual roll of rifle fire is made up of individual explosions.

Experiments

1. Perform the experiment mentioned on page 27.

2. Provide a round-bottomed flask (about 350 c. c.) with a rubber stopper (one hole), a glass tube, and a small piece of rubber tubing with a clip. The flask must be dry. Immerse it in boiling water for ten minutes with the clip open. Close the clip and cool under ice-cold water. On opening the clip cold water rushes in. See that the levels of water within and without are the same. From the volume of water that enters estimate the expansion per cubic centimetre on heating air from 0° C. to 100° C.

3. Determine the amount of copper displaced by 1 gm. of magnesium in copper sulphate. Weigh out 0·2 gm. of magnesium ribbon, perfectly bright and clean. On dropping it in small fragments into the copper sulphate and gently warming it dissolves completely and copper is deposited. Wash this copper with a gentle stream from the tap, then dry. Find weight of dried copper.

4. Try the experiment mentioned (p. 32) upon the Brownian movement.

5. A thin glass bulb in the centre of a tube has one side of its walls flattened by heating and slight pressure upon a carbon block. The tube is fitted at either end with a rubber tube and clip. The bulb is placed under the $\frac{1}{2}$-in. objective of a microscope, and light from an arc lamp is concentrated by a lens, placed at one side of the microscope, on the centre of the bulb. If now tobacco smoke is blown into the tube and the clips then closed, on focusing the microscope and adjusting the light, the Brownian movement of the smoke particles can be clearly seen.

6. Make a suspension of arsenic sulphide by grinding this

substance in a mortar, adding water from time to time. Find the density of this suspension (1) by weighing in a density bottle, (2) by the hydrometer.

CHAPTER IV

THE CLASSIFICATION OF THE ELEMENTS

The first duty of a scientist is to collect information, and his second to classify that information. By the beginning of the nineteenth century there was a considerable knowledge of the properties of substances, but that knowledge was largely un-coordinated. Compounds could always be classified according to the elements of which they were composed. For instance, blue vitriol being a compound of copper could be classed with other compounds of copper such as verdigris. A satisfactory method of arranging the elements, however, was more difficult to find. We may note that the essential feature of a good classification is that similar elements are grouped together and unlike elements separated from one another.

The first attempts were somewhat clumsy. Lavoisier and others had their systems, but most chemists merely divided the elements into metals and non-metals. There was also an intermediate class of " metalloids " which had some of the characteristics of metals and some of non-metals. These classes are too big. Animals may be divided into flesh-eaters and plant-eaters, but the size of the classes and the existence of animals that will eat both meat and vegetables, make the classification of little general use.

The existence of families of elements had, however, been noticed. Thus chlorine, bromine, and iodine were

seen to have similar properties and to form similar compounds. In 1829 Döbereiner pointed out that the atomic weight of bromine was approximately the average of the atomic weights of chlorine and iodine.

		At. Wt.		Difference.
Chlorine	..	35·47	....	—
Bromine	..	78·38	....	42·91
Iodine	..	126·47	....	48·09

Similar relations were found in the groups,

Calcium	Lithium
Strontium	Sodium
Barium	Potassium

the atomic weight of the middle element lying approximately half-way between those of the other two elements in the group. The family nitrogen, phosphorus, arsenic, antimony, and bismuth was also well marked. In some "triads" the atomic weight varied very little, e.g. nickel, 59; copper, 63; zinc, 65.

Thus there accumulated isolated pieces of evidence that chemical properties and atomic weight were in some way connected. Although the evidence was not sufficient to attract the attention of all chemists, yet there were some, notably Dumas, who devoted their energies to following the clue. Dumas was one of the first to free himself from the half-superstitious belief that three was the number of which all families of elements consisted. By dealing with larger groups he was able to see more clearly the relations of the atomic weights. One family showing a gradation of properties has already been mentioned, namely:

Nitrogen.	Phosphorus.	Arsenic.	Antimony.	Bismuth.
14	31	75	119	209

Dumas suggested that the atomic weights should be represented thus:

Nitrogen	..	$14 = 14$
Phosphorus	..	$31 = 14 + 17$
Arsenic ..	..	$75 = 14 + 17 + 44$
Antimony	..	$119 = 14 + 17 + 2(44)$
Bismuth	..	$209 = 14 + 17 + 4(44)$

Other families were dealt with in the same way. The connexion between chemical behaviour and these numbers was still obscure, but it seemed certain that there must be some relation between chemical properties and atomic weight.

One important result followed from these endeavours. It was essential that the atomic weights should be known as accurately as possible, and we owe to the workers of this time the first accurate determinations of many atomic weights.

A new method was adopted by Newlands. He wrote down a list of the elements in the order of their atomic weights, starting with hydrogen, the lightest. Having got the elements in order, he paid no immediate attention to the actual atomic weights, but concerned himself only with the position of elements in the list. He found that elements of the same family were separated either by seven or by fourteen elements belonging to other families. "In other words," he says, "the elements of the same group stand to each other in the same relation as the extremities of one or more octaves in music. Thus in the nitrogen group, between nitrogen and phosphorus there are 7 elements; between phosphorus and arsenic, 14; between arsenic and antimony, 14; and lastly between antimony and bismuth, 14 also."[1]

It will be seen by reference to the table at the end of

[1] *Chemical News*, 18th August, 1865.

the book that the numbers are now 8 and 17 instead of 7 and 14. The elements of group 0 were not known in Newlands' time, and he bracketed together some elements (e.g. cobalt and nickel) and treated them as one.

It seems then that if the elements are arranged in the order of their atomic weights, similar properties recur at regular intervals much as similar tones recur at regular intervals in the musical scale. Not all the relations, however, were as striking as those of the nitrogen family. Indeed it could hardly be expected that the "Law of Octaves" would hold through all the elements, for there were no spaces left for undiscovered elements, so that elements with high atomic weight were placed too high up the list.

Newlands' suggestions were made timidly, and, in the absence of strong evidence in their favour, they were laughed at and forgotten.

In 1869 Mendeléef, a Russian, published conclusions similar to those which Newlands had put forward four years earlier. In the same year a German, Lothar Meyer, also showed that many properties recurred at intervals in the series of atomic weights. One such property is atomic volume, or the amount of room taken up by an atom compared with that taken up by an atom of hydrogen. The atomic volume of an element is obtained by dividing the atomic weight by the density.

A curve, after that by Lothar Meyer, is given in fig. 10. A mere glance at the curve is sufficient to show that high atomic volume recurs at intervals. If we follow the curve from left to right we find that atomic volume increases to "peak" values and then falls, to rise again later in the series. In each "trough" of the curve is a succession of elements differing little in atomic volume.

Atomic volume is not in itself a very interesting property. The value of Meyer's curve lies in the fact that it

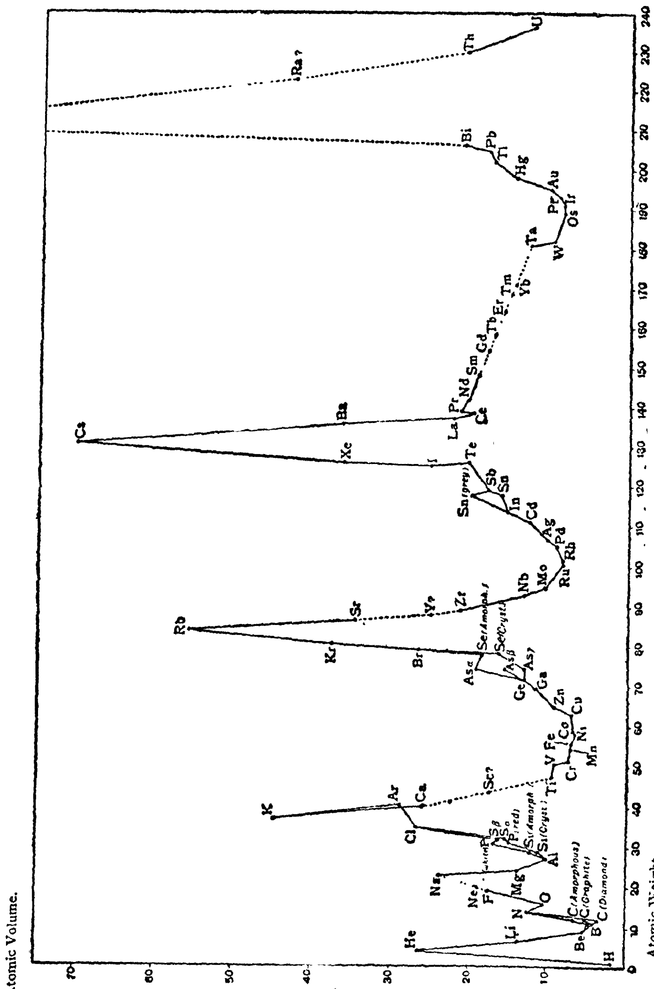


Fig. 10.—Atomic Volume Curve

shows the periodic recurrence of other properties besides atomic volume. For instance, in the order of atomic weights there are groups of elements that have high

melting-points, e.g. carbon, iron, platinum. All these elements are either at the minimum or just before the minimum points of the atomic volume curve.

All the non-metals occupy the ascending portions of the curve. The peaks are occupied by the metals most active chemically. In general, elements of the same chemical family are placed on similar portions of the curve. The elements of the nitrogen family will be found at the beginning of each steep ascent. The property of forming coloured salts is not confined to one family, but it is found only in those elements which lie in the troughs of the curve.

Many properties, therefore, recur periodically, and if nothing else were known about a particular element except its atomic weight, it would be possible to forecast its other properties.

Mendeléef, in 1871, published a paper on "The Periodic Law of the Chemical Elements" and gave a table showing the position of all the elements then known. He left many gaps for undiscovered elements and boldly predicted their properties. When some of these elements were subsequently discovered, his predictions were found to be startlingly accurate.

In order that elements having similar properties should be placed in the same family or group, it was necessary to take some elements out of the strict order of atomic weights. Mendeléef roundly asserted that it was the atomic weights that were at fault. When the atomic weights were investigated more carefully it was found that in all but two cases his confidence was justified. The two anomalies, viz. the placing of tellurium before iodine and of cobalt before nickel, together with a third which arose later, have since been explained on other grounds (see Chapter XIV).

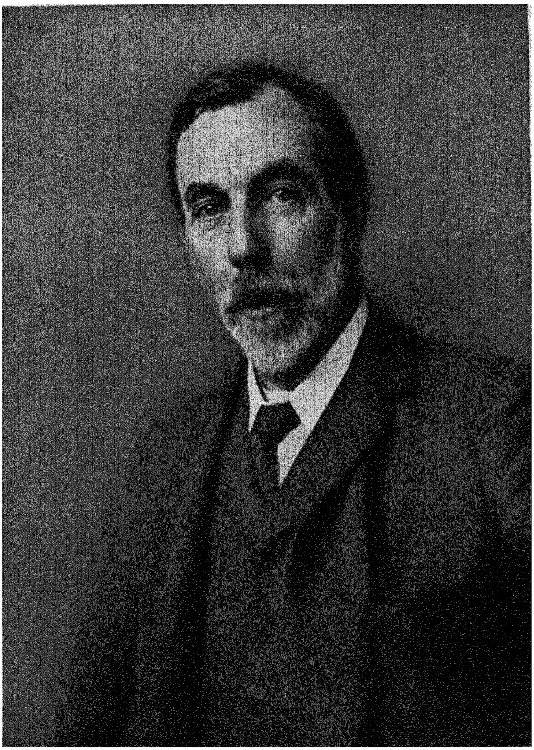
The Periodic System classifies a large number of facts.

It also predicts new ones, and the accuracy of its forecasts strengthens our belief in the table. There is one more test. Any new elements discovered must find places in the system or the system is wrong. Our calculations would be upset if a new element were discovered with an atomic weight 13, for there is no room between carbon (12) and nitrogen (14).

There was promise of a difficulty of this nature towards the end of the last century. Lord Rayleigh and Sir William Ramsay discovered argon in the air and found its atomic weight to be 39·88. There was no vacant place between potassium (39·10) and calcium (40·07). Indeed there was no vacant place anywhere near where one was required. It had, however, occurred to Lord Rayleigh that there was room between chlorine and potassium.

When Sir William Ramsay was looking for argon in the gases given off when the mineral clèveite was dissolved in acid, he found that helium was present. Sir Norman Lockyer, in 1868, had found by means of the spectroscope that an element unknown on the earth existed in the sun. This element was called helium. Ramsay discovered it on the earth, also by means of the spectroscope, in 1895. The new gas was purified and its atomic weight found to be 3·98. It required a place, therefore, between hydrogen and lithium.

The difference in the atomic weights of helium and argon is therefore 36. This difference is approximately the same as that between the atomic weights of elements of the first series or "octave" and those of the elements of the third series, e.g. lithium (7) and potassium (39); carbon (12) and titanium (48); fluorine (19) and manganese (54). Ramsay therefore expected to find a gas similar to argon and helium, having a place in the second series and of atomic weight about 20. He discovered such a gas in 1898 and named it "neon" (new). A



Elliott & Fry

SIR WILLIAM RAMSAY

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little before he had discovered "krypton" (hidden), and a little later he obtained "xenon" (the stranger). The five gases are all present to a small extent in the air. They are very much alike in properties. From the chemist's point of view they are alike in having no properties. They cannot be made to combine with anything. Even when heated to the highest temperatures in contact with the most active substances, such as sodium, phosphorus, and fluorine, they are quite unaffected.

Since they resemble one another but differ from all other known elements, it is clear that they must form a group by themselves. The atomic weights show that the group must come before group 1, as was expected by Lord Rayleigh. It is necessary, therefore, to place argon (39·86) before potassium (39·10) and so to create a third anomaly in the system similar to those mentioned on p. 49.

The following facts show how well the Periodic System emerges from the test imposed upon it by the discovery of the inert gases. The group number also expresses the valency of the elements towards oxygen or chlorine. Thus the elements of group 7 can combine with a maximum of seven atoms of chlorine, those of group 6 with six atoms of chlorine, and so on down to the elements of group 1, which can combine with one atom of chlorine. The series would be complete if the elements of group 0 combined with no atoms of chlorine. As already stated the argon gases cannot be made to combine with chlorine or anything else. These new gases then find their place in the system even though there was no obvious position waiting for them.

It was stated at the beginning of this chapter that a scientist had to collect facts and then to classify them. A good classification should be more than a convenient card-index; it should give us some idea of the principles underlying the facts. The Periodic Classification enables

us to see that chemical properties and atomic weight are to a great extent connected. The system, however, is not perfect. There is no exact relation between the atomic weights of the elements of the same chemical family. For instance, the recently determined atomic weight of bromine (79·92) is not exactly midway between those of chlorine (35·46) and iodine (126·93). Further, the system brings into prominence certain relationships, such as the number of chlorine atoms with which the elements of the different groups can combine, but it neglects other relationships of almost equal importance. It accounts satisfactorily for the argon gases, but it fails to account for the "rare earth metals". These metals, more than a dozen in number, possess very similar properties and have to be crowded into the two places in the table between barium and tantalum. (We know now that they have to be crowded into only one place in the system.)

The three "anomalies" have already been referred to (p. 49), namely, that argon has to be placed before potassium, cobalt before nickel, and tellurium before iodine. The atomic weights have been very carefully determined and there seem no grounds for supposing that greater accuracy in finding the atomic weights can alter the order of the elements. What is the explanation?

Other questions arise. As pointed out by Prout in 1805, the atomic weights of most elements are almost whole numbers. This can hardly be due to chance. What is the reason? Is the atomic weight the fundamental quality of the atom that the periodic system supposes, or is there some deeper quality which fixes both the atomic weight and the chemical behaviour of elements? How far these questions have been answered during the last twenty years is discussed in later chapters.

CHAPTER V

ON SCIENTIFIC METHOD

Science is not merely knowledge, but organized knowledge. The vast collection of facts by the alchemists, some of them trivial and some of the utmost importance, did not produce a science called chemistry.

The science of entomology is best served, not by the pinning of innumerable butterflies and moths in boxes, in joyous record of their hunt and capture in a sunny glade or at the treacle-smeared tree trunk, but rather by the patient study of the life history of these specimens. And in this study what infinite pains must be taken to separate the relevant facts from the irrelevant. Accurate observation is the basis upon which the fabric of science is built; but, having made his observations and gathered his rich harvest, the scientist finds that his work is far from complete. He is possessed of knowledge, some trivial and some of the greatest importance; from isolated facts he must advance groups of facts which are causally connected. To know these causes he must recognize the really significant facts; how is this to be done? Henri Poincaré makes the following observations on this question: " Scientists believe that there is a hierarchy of facts, and that a judicious selection can be made. . . . The most interesting facts are those which can be used several times, those which have a chance of recurring. . . . Suppose that instead of eighty chemical elements we had eighty millions; . . . each time we picked up a pebble there would be a strong probability that it was composed of some unknown substance. Before each new object we should be like a new-born child. In such a world there would be no science."[1]

[1] *Science and Method*, translated by F. Maitland (Nelson).

The constantly recurring facts give us the key to many difficult situations. If we find that fact A occurs persistently, and is invariably accompanied by fact B, we may *assume* that A and B are causally connected. Such " reasoning " no doubt gave rise to many an old saw of the weather prophets. " The oak before ash only a splash, the ash before oak a terrible soak." So ran the old proverb. Or again, red berries in quantity foretell a hard winter. But because on several occasions a hard winter has been known to follow an abundance of autumn berries, it does not follow that these two phenomena are causally connected. What further evidence must we have to establish such a connexion? We must show that, not only is a hard winter *always* preceded by abundance of berries, but also that a mild winter never follows this abundance, and that a hard winter is never experienced when the berries are few. All of which seems perfectly clear to us in the light of the present century, though it was by no means apparent to our forefathers.

Again, in the A and B case mentioned above, it may so happen that the B fact has not been established by observation, but rather perceived " intuitively ". In other words B is a convenient lie told to account for A. Virgil and Aristotle in their writings both mention the mason bee, which flies carrying with it a small fragment of earth or stone—fact A. Both these writers state that by these loads of earth or stone which they bear the bees are able to steer a straight course against the wind—supposed that they accomplish their journey by this means, without being blown from their course—B. Now B in this case is only a surmise—the idea, clothed in poetic garb, may be attractive, but utterly untrue. Would the bees be any the less deviated from their course by opposing to the wind a greater surface, that of the load, by which also their speed must be decreased?

Still, if such a suggestion is absurd, what is the reason for carrying such loads? The answer was given by Swammerdam two thousand years later. He took careful observations and found that the stones were actually built into the hives by the bees to strengthen their homes against sudden storms. Here, then, is the real fact B, the connecting link with A; it was established by observation and not surmise.

Now there are several lessons to be learnt from this illustration of the bees. In the first place, science is not a thing of belief, it deals with hard facts. The latter may be hard to come by, they may escape us altogether, unless we happen to be looking for them. But if science is not a belief, how can its progress be accounted for—from the groping stage of ignorance, to the full light of modern discovery? Faraday, when watching the experiments of others, would ask them: "What am I to look for?" How do we know what to look for, what is significant and what unimportant if we have no belief, and no opinion about what will happen? The answer is that hypothesis and belief are two utterly different things. These two in mediæval times were, so far as science was concerned, completely one. We can picture Galileo dropping the two weights from the top of the tower at Pisa. One weight is one hundred times the other, yet they both fall together at the feet of the university professors assembled below. This is the first time that one had dared to question the word of the mighty Aristotle. So great is its influence that the professors refuse to believe their eyes. They walk away with hatred for the meddlesome Galileo. For them the utterances of the great philosophers of Greece have become a creed. Of course the heavier weight falls 100 times as fast as the other; it were heresy to believe otherwise. We have already seen that Aristotle advocated the use of the hypo-

thesis (see Chapter I) but utterly failed to verify by any experimental evidence the conjectures which he made. We can well imagine the astonishment of the Greek sage on finding that his lightest words were taken so seriously!

In the second place, we learn from the illustration that the observation of facts and their classification is the basis of scientific progress. Again the unquestioned authority of Aristotle would doubtless check any investigation as to the destiny of the burden of stones carried by the bees, until someone, with more independence of thought and action, sets himself the task of long watching, rewarded by discovery.

Thirdly, we learn from it that success in science is won, not by violent partisanship of one hypothesis or the other, but by the persistent though passionless analysis of every phenomenon brought to light by observation. Swammerdam had carried on for months his observation of the bees, in spite of the fact that, in 1673, the dykes in Holland had been cut, to check the French invasion—with corresponding ruin to the hives. It is that power of maintaining a balance, a mental reservation which can be neither rushed nor persuaded into passing judgment upon insufficient data, which is the birthright and characteristic of the scientific mind, both to-day and in past years.

Tracing the causes of phenomena was a very difficult matter for the early Greek natural philosophers. We have already seen that an inquiry into the actual happenings was to them a far less inviting task than the invention of possible reasons for their occurrence. "Nature abhors a vacuum"; how well that sounded to the philosophic ear! Yet no tangible evidence as to the truth or falsehood of such a statement was made until the contribution of Torricelli with his so-called vacuum (see p. 14).

Now why was this causal connexion between facts so difficult to establish? We must remember that the scientific experiment as we understand it to-day was not an instrument of inquiry of any recognized value until the time of Sir Francis Bacon. It is well to state what is the exact significance of the term experiment. It is an attempt, by an artificial arrangement of the conditions, to discover the cause of any scientific happening. As an example let us take the case of the rusting of iron. It is found that when iron is left in the air a red coating of rust is formed upon it. Are all the ingredients of the air concerned with the rusting of the iron or only some? The air contains oxygen, nitrogen, and water vapour, let us say; what causes the rusting? We enclose iron in a given volume of air over water, and find that water rises to a certain volume in the enclosure, and there remains; that the red rust is formed; and that, when we test the gas left above the water, it no longer contains oxygen but consists for the most part of nitrogen. We therefore learn that oxygen is concerned in the rusting but nitrogen is not. But what about the water vapour, is that concerned too? If we place bright iron nails in absolutely dry air they will not rust. Here we have the phenomenon A taking place in the presence of B, water, and the non-occurrence of A in the absence of B. Therefore, by arranging the conditions we have shown that A and B are causally connected.

This method of experiment, so essential in modern science, was a thing of slow growth. In the hands of the early experimenters it became a powerful weapon. The work of Lavoisier, in which he set himself to find out whether water can be changed into earth, affords a good example of the experimental method. Van Helmont had grown a willow in 200 lb. of earth under a hood to keep out the dust. The tree was fed with distilled

water only, but after five years it was found to have gained 164 lb., whilst the earth had lost only 2 oz.! It was concluded, therefore, that water had turned to the solid material of the willow. (A logical person would say, "You have not excluded every other possible cause of the tree's gain in weight; for instance, the air might contribute something for which no allowance has been made." Quite true, but knowledge concerning the air was very limited at the time, and its action in feeding the tree was unsuspected.)

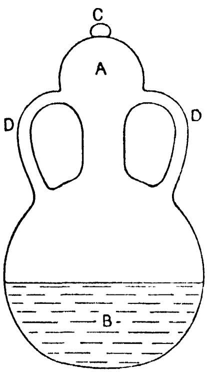


Fig. 11

Lavoisier started his investigation by distilling rain-water; he finds that an earthy residue is formed, and that the density of the distilled water is practically the same as that of the rain-water. This residue may come from: (1) something outside the distilling vessel, (2) from the vessel alone, (3) from the water alone, (4) from both the vessel and the water.

In his investigation Lavoisier heated water in a glass pelican 100 days. This instrument (fig. 11) consisted of two glass bulbs A and B. The liquid was poured in at C, which was hermetically sealed. The water in B was boiled and converted into steam, which condensed in the bulb A, returning to B by the two channels DD. After the heating he found: (1) That the pelican and water together weighed the same, showing that nothing had been received from without. (2) On taking the water out of the vessel it was found that the latter had lost in weight. (3) When the water was evaporated a solid residue was obtained whose weight *was equal to the weight lost by the vessel.* Lavoisier concluded therefore that the greater part of the earth separated from rain-water is due to the solution

of the vessels in which it has been collected and evaporated.

Here then is a successful attempt to arrive at a cause (the cause of the residue) by a direct measurement of weight. It was the employment of such measurements involving the use of the balance that put chemistry on the level of an exact science.

Another example of cause tracing, the discovery of argon, is worth consideration, as it depends upon highly exact determinations, such as are possible with modern methods and apparatus. It also illustrates the use of hypothesis, which is the characteristic of scientific method to-day. (By hypothesis we mean a *provisional* explanation of anything whose correctness is to be tested *deductively* by reference to facts.)

To take an instance apart from " science ". In Charles Reade's *The Cloister and the Hearth*, after the terrible struggle with the thieves and murderers at the inn, Denys finds the wretched landlord hiding in the cellar. He rakes over a heap of rubbish and finds what appear to be human bones, and speaks as follows to his companion.

" True, mate; but yon knave's ashy face is as good a light to me as a field of battle. I read the bone by it. Bring yon face nearer, I say. When the chine is amissing and the house dog can't look at you without his tail creeping between his legs, who was the thief?"

Just as the dog's cringing attitude betrayed his guilt, so the landlord's ashy face betrayed his, making it worth while to probe further into the rubbish heap.

Now this has all the qualifications of a good hypothesis. First, it must, on the face of it, be a reasonable supposition, capable of proof or disproof.

Secondly, it must apply to undiscovered facts. If the man was guilty other evidence would be forthcoming—the finding of a human skull, as the story goes on to tell.

Thirdly, facts can be deduced from it and tested; the evidence of the bones established the landlord's long-standing habits of robbery and murder, and his abuse of his position of host, &c.

The hypotheses from which science acquires its growth are not always so clean-cut as the above example, although their qualifications must be the same. Moreover, there are frequently many provisional explanations of the facts which will require to be considered.

Lord Rayleigh and Sir William Ramsay carried out exact determinations of the density of nitrogen. They found that the weight of 1 litre of nitrogen obtained from the air was always heavier than the weight of a litre of nitrogen obtained from chemicals; the latter nitrogen was about $\frac{1}{2}$ per cent lighter. The measurements were taken with the greatest accuracy and many times, so that this difference in weight was known not to be due to experimental error.

There are many hypotheses possible to account for this difference. (1) The substances might contain impurities which cause such a small difference in weight. (2) In the chemically derived gas some of the molecules might be split up, thus decreasing the density, for a particle half the weight of the molecule might occupy its place. (3) The heavier gas is a mixture of nitrogen and a gas of greater density. (4) The lighter gas contains nitrogen and an ingredient lighter than nitrogen.

Which of these guesses is right? That can be found only by the evidence of experiment. The first hypothesis was rejected after rigidly purifying the two gases. The second likewise, by showing that, after keeping the gas for months, its density was found to be unaltered. Both gases were previously submitted to silent electric discharge which, as in the case of oxygen (see experiments) will tend to condense the molecules.

There remain the hypotheses of mixture. If they are correct it should be possible to remove nitrogen and leave behind the unknown gas. Further, we can deduce that, in order to obtain a gas $\frac{1}{2}$ per cent heavier than the chemical nitrogen (as in hypothesis 3) a volume of 1 per cent of gas $1\frac{1}{2}$ times the density of nitrogen would be required.

The substance chosen for the removal of nitrogen was magnesium. The nitrogen obtained from the air was passed over the heated metal several times, its density gradually increased to a maximum, at which point all the nitrogen had been absorbed, and a gas of density 19 was left.

To test hypothesis 4, the chemical nitrogen, the lighter variety, was treated with heated magnesium; it was all absorbed with no residual gas.

Therefore the truth of hypothesis 3 is established. The experiment whose evidence decides between two hypotheses, establishing one and disproving the other, is called the *crucial* experiment; in this case it was the treatment with heated magnesium.

When the results of this investigation were described at the Oxford meeting of the British Association in 1894, they met with much criticism. It was difficult to believe that an unknown gas had existed in the air—to the extent of 1 per cent—without having been discovered. It was stated above that a good hypothesis will lead to new facts by deduction, and the discovery of this gas is actually what was deduced. In 1785 Henry Cavendish had explained before the Royal Society his experiments on the action of the electric spark upon the air. He showed that when a spark passes between two platinum wires sealed into a glass flask, a red gas was formed. This gas could be absorbed by an alkali such as caustic potash, the liquid rising in the vessel A. If more oxygen is added

to the gas in A and the sparking is prolonged all the nitrogen can be combined to the red gas, which is absorbed in the alkali. At last only oxygen remains and this can be absorbed. (Cavendish used liver of sulphur.) There is a small bubble left *which cannot be absorbed.*

Here is a modern form of Cavendish's apparatus (fig. 12). The platinum wires CC are sealed into the flask A, which is inverted over a solution of caustic soda in B. On sparking by means of an induction coil a red gas is formed which is absorbed by the liquid in B, which rises. Oxygen is added from time to time through the mouth of the flask in such quantity that the level to which the liquid rises is kept below the platinum wires.

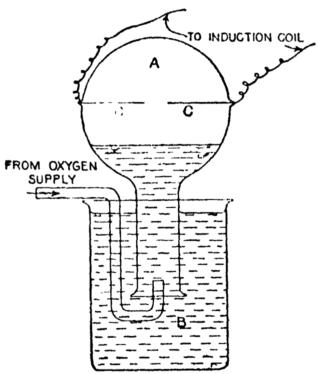


Fig. 12

Rayleigh and Ramsay, referring to Cavendish's communication, stated that the bubble of unabsorbed gas was not due to experimental error as Cavendish had supposed, but was a new gas. To test this Lord Rayleigh subjected air mixed with oxygen to an electric flame in the presence of potash, and obtained 2 litres of the gas subsequently called argon.

But by proving conclusively that water is not converted into earth, that air contains an inactive gas other than nitrogen, and by the acquiring of a hundred other detached fragments of knowledge, we cannot build up a science. Encyclopædic knowledge does not produce a science, any more than does a French dictionary produce the French language. The facts must be classified.

Some one property may be used as a basis, and upon it all the objects or all the phenomena possessing it may be assembled. In this manner the like are separated from the unlike. If we recognize the common nature belonging to a greater or lesser number of facts and extend this community of nature to other unexamined cases we are "generalizing". Generalization gives us law. A scientific law is not at all like a legal enactment, it is a statement of a relationship which holds between certain classes of facts.

When we state that all acids have hydrogen in their composition which can be replaced by a metal, we are making a qualitative statement about acids, a generalization which ranks as a scientific law.

We have already considered various quantitative laws, such as the law of volumes of gases. There is another good illustration of a quantitative law in Snell's law of refraction. He discovered in 1621 that when light passes from one transparent material to another it is bent out of its course. Snell showed that there is a definite relationship between the sine of the angle which the ray of light makes with the perpendicular in one substance, and the sine of the angle made by it in the second substance, that the one sine divided by the other is always the same for two substances such as air and water *for all angles.*

$$\frac{\text{Sin}\phi}{\text{Sin}\phi'} = \text{a constant for all values of } \phi \text{ (fig. 13).}$$

In making such a statement it was obviously quite impossible for Snell to try all substances, and all values of ϕ; his was a generalization. That general statement has never been found to be at fault in any of the innumerable cases to which it has been applied since Snell's time.

(We have seen that the growth of a science involves

the collecting of facts by observation and induction, the assigning of their causes by hypothesis and deduction, and the classification of these facts and the formation of generalizations or scientific laws. But there is another way in which the instrument of hypothesis may be used: to guess at the existence and properties of things beyond our senses, and, as M. Perrin says, " to explain the complicated visible by the simplicity of the invisible ". It was this use of hypothesis which, through Dalton, gave

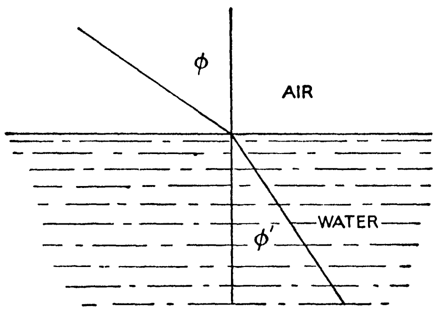


Fig. 13

us the atom. Again, it was purely as a hypothesis that the molecules of organic compounds such as the paraffins were supposed to be linked together as a chain. No one had ever seen such a chain structure, and yet its existence has been definitely established in the realm of fact. Observation and inference will always be the deciding factors in scientific progress, yet there is room for pure reason beyond the range of observed fact.)

Experiments

1. Place some bright iron nails in a flask containing dry air. Suspend them from the cork at the mouth of the flask, the bottom of which is covered with lumps of quick lime. What is the appearance of the nails after several weeks?

2. Place the bright nails in a flask completely filled with distilled water, which has been boiled thoroughly to expel all air. The flask is firmly corked. Is there any appearance of rust in a week's time? Compare the nails in the water with some which have been exposed to the ordinary moist atmosphere.

3. Try the effect of the silent electric discharge upon oxygen. A wide tube B (fig. 14), the horizontal portion 30 cm. long,

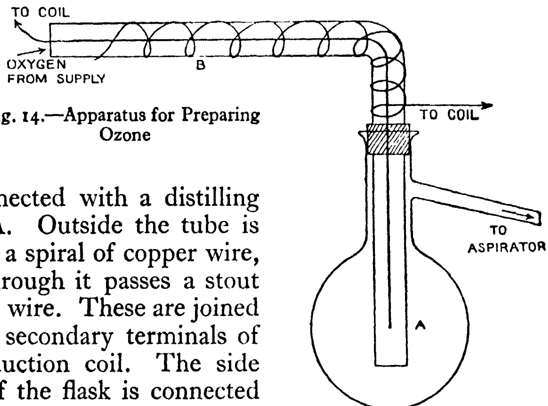


Fig. 14.—Apparatus for Preparing Ozone

is connected with a distilling flask A. Outside the tube is wound a spiral of copper wire, and through it passes a stout copper wire. These are joined to the secondary terminals of an induction coil. The side tube of the flask is connected to an aspirator, and a slow stream of oxygen is drawn through the tube. After the discharge has passed for a little time remove the tube B. You will notice the peculiar smell of ozone. Try its effect upon (*a*) starch-potassium iodide paper, (*b*) mercury. It is much more active than oxygen. By volume experiments difficult to perform it has been proved to be a condensed modification of oxygen. This was the condensation that Rayleigh and Ramsay tested for in the case of nitrogen (see p. 60).

4. Try the effect of the electric spark upon air in the apparatus explained in the chapter. Do you get a rise in the level of the alkaline liquid? On adding oxygen and sparking does the contraction continue?

N.B.—Excess oxygen can be removed finally by adding pyrogallic acid to the alkaline solution and sparking the flask under the liquid.

CHAPTER VI

ELECTROSTATICS

The discovery that a piece of amber which has been previously rubbed will attract light bodies was made in very early times, and is usually attributed to Thales of Miletus. It was owing to this property which amber possesses that William Gilbert in the days of Queen Elizabeth introduced the word electricity for similar powers of attraction of other substances for light bodies. The name electricity is derived from ἤλεκτρον, amber.

If we balance a box-wood ruler on the bottom of a round-bottomed flask, and bring near to it a piece of vulcanite which has been rubbed—either with cloth or fur—the ruler will be attracted, and can be gently rotated in a horizontal plane. The vulcanite does not touch the ruler at any point, yet it exercises an attraction for it. Here, then, is an example of "action at a distance". When a force is transmitted from one body to another, we are accustomed to think of some link between the two bodies. We should not expect the steam tug to pull the great liner out from its mooring into the harbour without the aid of the connecting hawser.

Now there are many cases of action at a distance without the connecting link being apparent. To give examples, there is the action of gravitation; the attraction of the north pole of one magnet for the south pole of another; the rise in temperature of a body when exposed to the rays of the sun, though the latter has no apparent link with the earth. Are we to assume that in all these cases there really is no connecting link, or must we assume that some medium does exist through which these actions can take place by the employment of some mechanism of which we are ignorant?

The first of these alternatives does not appear reasonable, it is difficult to see how the daily miracle of sunrise with its attendant tribute of heat and light can take place if the earth is absolutely isolated from the sun—if there is nothing in between. The supposed medium in which and by which these phenomena can occur is called ether, which pervades both matter and space.

The velocity of light is the same as that of the electric current, and there is strong evidence that light, electrical, magnetic, and gravitational forces are all transmitted by the ether.

In the case of gravitational force, it was shown by Sir Isaac Newton in his Law of Gravitation that every body attracts every other body with a force that is proportional to the mass of the bodies and inversely proportional to the square of their distance apart.

$F \propto \frac{mm_1}{d^2}$, where F is the gravitational force, m and m_1 the masses of the bodies, and d their distance apart.

If $F \propto \frac{mm_1}{d^2}$, there will be some value of the expression $\frac{mm_1}{d^2}$ to which F is equal.

Therefore $F = f\frac{mm_1}{d^2}$, and f is a *coefficient*, such that when $\frac{mm_1}{d^2}$ is multiplied by it the force F is obtained.

Now the law stated above applies equally well in the case of electrified bodies. Let us take a few simple cases of electrification first of all. A vulcanite rod is electrified by rubbing, and placed in a stirrup suspended by a silk thread. If another rubbed vulcanite rod is brought near to it a strong repulsion is shown between them.

If, on the other hand, a glass rod, which has been previously heated in an oven to dry it thoroughly, is rubbed with silk, and this is brought near to the sus-

pended vulcanite rod, the latter will be strongly attracted.

From this we learn that bodies made of the same material repel each other when electrified by the same means. However, it is possible to cause an attraction between other bodies of different material. Further, if rods of vulcanite, shellac, sealing-wax, resin are electrified they all show mutual repulsion, but all will attract glass electrified with silk. Similarly, glass rods, on electrification, show mutual repulsion.

Du Fay, in the eighteenth century, in order to account for these facts, suggested that there were two kinds of electricity: vitreous, such as is obtained from glass; and resinous, from vulcanite or sealing-wax. Benjamin Franklin suggested the " one-fluid " theory. According to him an uncharged, i.e. an unelectrified, body contained the normal amount of fluid: if it was endowed with the same kind of electricity as glass, i.e. vitreous electricity, it was positively charged and contained an excess of the fluid; if, on the other hand, its electricity was resinous, it contained less than the normal supply of the fluid and was negatively charged. This theory of Franklin's, as you will see later, resembles very strongly our modern methods of accounting for the facts of electricity. According to Franklin, matter took the place of a negative electric fluid, and the particles of matter and of his electric fluid *had a strong attraction for each other.* When you rub a rod of vulcanite on your coat sleeve, according to Franklin, you are removing the electric fluid from the rod, so that the latter can attract; according to the present theory you are adding electrons to the rod, and these are capable of attracting.

Since the attraction and repulsion were known facts, and belonged to that class of phenomena known as action at a distance, it was thought that the repulsion between two particles of like charge obeyed a law such as that of

gravitation. F, the force of attraction, should be proportional to the charges of electricity upon each body, and inversely proportional to the square of their distances apart.

$F \propto \frac{cc'}{d^2}$, where cc' are the charges and d is the distance between the centres of the two bodies. The *direct* proof of this generalization is difficult, and can be established only approximately. Since the electricity is distributed over the surfaces of the two bodies (see experiments) there is the disturbing effect of non-uniformity of distribution. Nevertheless, this inverse square law was established by Cavendish, and, at a later date, by Maxwell.

Since $F \propto \frac{cc'}{d^2}$, as before, $F = f\frac{cc'}{d^2}$, where f is a coefficient.

How are we to arrive at the significance of this coefficient?

Two pieces of elder pith (such as is used in cutting botanical sections) are covered with gold leaf and adjusted until their weight is the same. (This can be done with a chemical balance by adding, when necessary, more gold leaf.)

Each is suspended by a thread of unspun silk; they hang vertically at the distance of 1 cm. from each other. Both are charged simultaneously with the same vulcanite rod. There will be a repulsion, and each thread will make an angle with the vertical which can be measured; knowing the weight, the repulsion in dynes can be found.

Let us assume that the repulsion between these fragments of elder pith is 1 dyne (approximately the force of gravity acting upon 1 mgm.). Each fragment has obtained the same charge. Let us further imagine that the distance between them is 1 cm.

Then we have $F = f\frac{cc'}{d^2}$, i.e. $1 = f\frac{cc'}{1}$; but $c = c'$;

therefore $fc^2 = 1$. If $f = 1$, then $c^2 = 1$, and $c = 1$.

Here then we have a reasonable unit of charge of electricity. It is that charge which, placed at a distance of 1 cm. from an equal charge of the same kind of electricity, causes a repulsion with the force of 1 dyne. We assume that in vacuo the coefficient f is unity.

Suppose the two charged fragments were suspended in a medium such as petrol, would the force of repulsion between them be the same?

It has been proved that the force would be considerably diminished. Let us say that it is reduced to $\frac{1}{2}$ of the original. Then $F = f\frac{cc'}{d^2}$ where $f = \frac{1}{2}$. To regain the old value for the force of repulsion we must increase the charges. In other words, owing to the substitution of petrol for air we have increased the capacity of the gilded fragments of pith for holding electricity.

The non-conducting medium through which forces due to electric charges can act is called the dielectric.

Generally, $F = \frac{1}{\kappa}\frac{cc'}{d^2}$, where κ is the *dielectric constant* of the medium in which the charges are situated.

We find that a charged body instantly loses its charge on being touched, either with the human body or with a large number of substances, including all the metals, wool, cotton, or any substance upon which moisture is condensed. Such substances through which electricity can pass are called *conductors*. On the other hand, the charge is retained if the charged body is in contact with an *insulator*, such as paraffin wax, sulphur, vulcanite, silk, oil. In these materials the eleetric charge is retained with very little loss. It must follow that the dielectric, petrol, considered above must be an insulator; if this were not so there would not be a stationary charge, nor a repulsion between two charges.

The testing of a body for electric charge consists in the recognition of a force of repulsion or attraction. For this purpose an electroscope is used. The apparatus is shown in fig. 15. It consists of a metal disc to which is attached at right angles a metal rod, terminating in a metal plate to which is attached a narrow strip of gold leaf. The rod is supported by a vulcanite insulator in a metal case with two sides of transparent glass. This case is provided with a binding screw on the right by which it can be connected to the earth. To the disc of the electroscope charged bodies can be brought, which thus (by contact) impart their charge. The leaf, being similarly charged with the metal rod and plate, diverges. A scale or a circular protractor can be placed in one of the glass sides of the electroscope for measuring the angle of divergence.

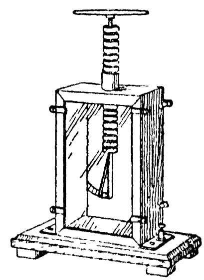


Fig. 15.—Gold-leaf Electroscope

By this instrument it can be shown that *both kinds of electricity are produced at the same time by friction, and in equal quantity.* A small indiarubber cap is placed over the end of a vulcanite rod. The latter is twisted in the cap two or three times. On placing rod and cap upon the disc of the electroscope there is no divergence of the leaf; but on removing *either* the *rod* or the *cap*, there is a strong divergence. The two charges neutralize each other, but on the removal of one of them, positive or negative electricity causes the divergence. Similarly it may be shown if *any two* substances are rubbed together, positive and negative electrification are both produced to an equal extent. There is no creation or destruction of electricity, only a transference; the *total quantity remains unaltered.*

There is another method of charging the electroscope besides the direct contact between its disc and the charged body. It is the method of *charging by influence*, discovered by Æpinus of Petrograd (then St. Petersburg) more than 170 years ago. An electric charge is spread uniformly over a spherical conductor but it cannot pass through an insulator. Nevertheless, it must exert an influence upon the dielectric surrounding it, otherwise it would not be able to attract light bodies to itself from a distance.

A rod of glass is rubbed with silk to give it a positive

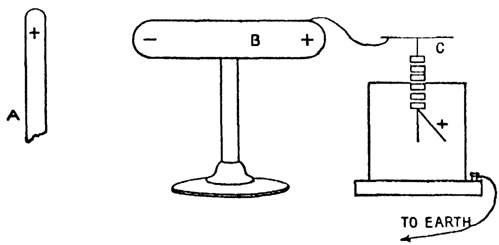


Fig. 16

charge. If now one of the fragments of elder pith supported on its silk thread is first positively charged and then gradually brought up to the glass rod we shall notice that the repulsion upon it will increase as the distance grows less (strictly, the square of the distance). Let us suppose that the pith has unit charge; the force of repulsion upon it, at any point as it advances to the rod, is the *electric intensity* at that point. So that there is a gradual falling off in the electric intensity due to the charge on the rod as the distance from it increases.

Suppose that the charged rod A (fig. 16) in the figure is brought near to an insulated conductor B, which is connected by a wire to the electroscope C. As the rod advances the leaf diverges; if the rod is removed the leaf

again collapses. The charge upon A apparently sets up a pressure electrically in the dielectric of the air [1] round it, which is transmitted to the conductor B. If we test the charge upon the leaf it will be found to be positive (it causes increased divergence with a known positive charge).

Suppose that when A is charged it is near the conductor B, and B is earthed by touching it. The leaf collapses. Connexion with the earth being broken, A is removed; the leaf again expands, this time with a *negative* charge.

In the earlier days of electrostatics it was suggested that the negative charge, produced upon B by influence or *induction*, was held bound by the inducing charge A. Though the positive charge at the other end of B could be earthed, that nearest to A could not, until, on the removal of positive charge A, it was free to spread over the whole surface.

Faraday made an imaginary but vivid picture of the state of affairs in the space between A and B. Imagine a small area on the surface of A, from which a number of lines of electric stress into the dielectric originate (Faraday's " lines of force "). These lines terminate on the surface of B, enclosing an area equal to that from which they started. The whole group of lines constituted a tube of force. If unit quantity of charge is distributed over each end of the tube, then it is termed a *unit* tube of force. According to Faraday these tubes tended to shorten, there was a tension upon them like that of a stretched thread of elastic. He further supposed them to be exerting a pressure at right angles to the sides of the tubes.

In fig. 17 the positively charged sphere A is acting inductively upon the sphere B, which is earthed; a negative charge is produced upon it. Each of the dotted

[1] Not to be confounded with air pressure.

lines represents the axis of a tube of force; the central line is straight while the rest are curved, owing to lateral pressure perpendicular to the sides.

If this is a true picture of induction, then, since the area of the tubes of force is the same at each end, it must

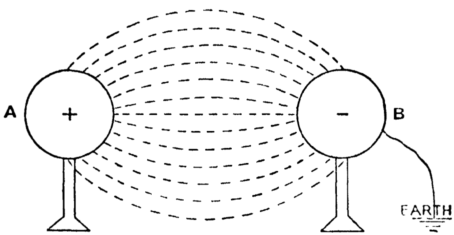
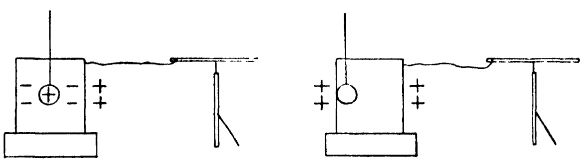


Fig. 17

follow that the inducing charge is equal and opposite to the induced charge. This was proved by Faraday by his famous "ice-pail" experiment.

A metal vessel (fig. 18 *a*) is insulated and connected with an electroscope. If a charged metal ball on an insulating handle is lowered into the vessel the leaf shows



(*a*) Fig. 18 (*b*)

divergence. If the ball is removed without touching the sides of the vessel the leaf collapses; for the negative and positive charges within and without neutralize each other. If, however, the ball touches the side before removal there is no collapse.

In fig. 18 *b*, when the ball touches the side the charge which it carries is exactly neutralized by the

induced charge on the inside; if this were not the case there would be an alteration in the divergence of the leaf. On removing the ball, the positive charge on the exterior of the vessel is left unaltered.

This hypothesis of tubes of force gives us an impression of stress and strain in the non-conducting media across which electrical influence can act. The strain produced is a very real thing; consider for example the formation of ozone from oxygen by it, and that series of oscillating displacements known as the wireless wave. The existence of such stresses in the dielectric brings us to the consideration of a new quantity.

A body, under the action of gravity, will always move from a higher to a lower level. In the same way we may regard a charge of positive electricity as endeavouring to move in the direction of the forces producing dielectric strain. In a conductor the movement meets with little opposition, whilst in an insulator it is prevented.

Consider the elder pith covered with gold leaf. Let us say it is positively charged, and is brought up to a positively charged sphere. At some distance away it will hang slightly out of the vertical, but as it is moved nearer, the angle which the thread makes with the vertical will increase. The work done in moving the pith through 1 cm. will constantly increase as the electric intensity increases.

That quantity whose *rate of increase* in any direction measures the electric intensity in that direction is called the *potential*.

Potential may be expressed in the following manner:

Let E = electric intensity and V = electric potential.

$$\text{Then } E = -\frac{dV}{dx}. \quad \therefore dV = -E dx.$$

Edx is the work done when unit charge is moved through an infinitesimal distance dx.

Suppose unit charge is carried from a to b in a direction everywhere coincident with that of the electric intensity. (Remember that E is a force.)

Then $-\int_a^b Edx$ is the total work done.

But $\int_a^b dV = -\int_a^b Edx$ and $V_a - V_b =$ the total work done in carrying unit charge from a to b.

Suppose that there are two points A and B in the

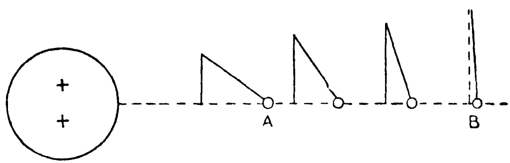


Fig. 19

journey of the elder pith as it moves towards the charged sphere, B being the more remote (fig. 19). The work done in moving unit charge from B to A equals the *potential difference* between A and B.

Again, consider a charged spherical conductor suspended in a large empty space. At a great distance the force due to it upon unit charge would be very small. According to the law of inverse squares, as the distance between the sphere and the unit charge decreases, the force increases. If the distance is reduced to $\frac{1}{2}$ the force becomes 4 times as great, if to $\frac{1}{3}$ it becomes 9 times, and if to $\frac{1}{n}$ it becomes n^2 times.

Fig. 20 shows the falling off of electric intensity with the increase of distance from O. The ordinates AB, CD are the potentials at points along the line. We cannot have any potential difference on the surface

of a conductor, any more than we can have a difference in level on the surface of a still pond. This is represented by the horizontal line EF. If any part of the conductor O were at a higher potential than another there would be a flow of electricity from one point to the other, until both were at the same potential. In an insulator such a flow is arrested, consequently there are inequalities of potential with corresponding electric strain.

This equality of potential at all points of a conductor enables us to realize what takes place in the case of charging by influence (see above.) There is a gradual fall in potential from A to B (as in fig. 20). At all points of B we have uniform potential; consequently at the end of B remote from A the potential is higher than it would be if B were an insulator. The positive charge supplies this necessary potential, and the electroscope shows divergence.

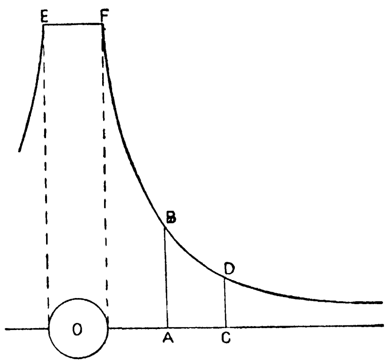


Fig. 20

That the surface of a charged conductor is an equipotential surface can be shown by experiment. If a wire is attached to the disc of an electroscope and the end of it attached to an insulating handle is made to touch the conductor at various points, it will be found that the divergence of the leaf will remain constant. In this experiment the case of the electroscope is earthed by a wire from the binding screw A; the divergence is proportional to the potential difference between the leaf and the earth.

If the conductor is spherical, equipotential surfaces will be a series of spheres whose centre is that of the conductor. So long as it *remains* on the same spherical surface, unit charge possesses the same potential energy at all points on that surface (cp. the potential energy of a weight raised above the ground). *No work* is done in moving it over the spherical surface of equipotential.

Now the amount of work done in moving unit charge from a point B to a point A nearer the charged conductor is proportional to the distance between A and B. So that even when the unit charge is very remote from the sphere there will be some repulsion upon it, and *some* work will have to be done in moving it; in other words, considering the action of the conductor alone, the potential can never be zero. For purposes of measurement the potential of the earth is taken as the standard zero; for, just as it is well-nigh impossible to alter the sea-level, so is it impossible to alter the potential of the earth.

Experiments

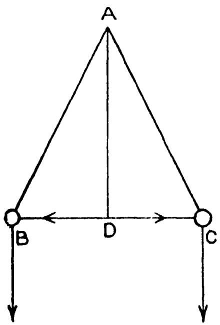


Fig. 21

1. Bring near to the ruler (p. 66) balanced on the flask a rubbed ebonite rod; there is an attraction. Do you get the same result with glass rubbed with silk?

2. Try the effect of sealing-wax rubbed with fur upon a few fragments of elder pith.

3. Show, by mounting the various rods of glass, ebonite, &c., in a stirrup suspended by a silk thread, that similarly charged bodies repel each other, whilst those with opposite charges attract.

4. Cut two small pieces of elder pith about the same size, cover them with gold leaf, and counterpoise on a balance; to each is attached a thread of unspun silk. Try the experiment mentioned above (fig. 21).

Hang the threads from a wooden stand so that the pith fragments are touching. On charging they separate, the threads making an angle with the perpendicular.

If distance between B and C is known the force of repulsion can be calculated.

Tension on string AB may be resolved into two components.

The vertical component is mg.

The horizontal component (due to repulsion between B and C) is $mg \tan\theta$, where m is the mass of B and $g = 981$ cm. per sec^2. Similarly for tension upon AC.

$\therefore$ Force of repulsion between B and C $= mg \tan\theta + m'g \tan\theta$.

Since B has same weight as C, $m = m'$.

$\therefore$ Repulsion $= mg\left(\frac{\mathrm{BD}}{\mathrm{DA}} + \frac{\mathrm{DC}}{\mathrm{DA}}\right) = mg\,\frac{\mathrm{BC}}{\mathrm{AD}}$ as threads are of equal length.

5. Connect a copper plate supported on paraffin wax to the disc of an electroscope by (1) silk, (2) cotton, (3) wool threads. What is the effect on charging the copper plate? Which is the best insulator, silk, cotton, or wool? Try the effect of moistening the threads.

6. Charging by induction (see p. 72). Try charging by induction, using a vulcanite rod and without the intervention of conductor B.

7. Faraday's ice-pail experiment. Use several metal vessels fitting one inside the other and each insulated from the next. If the ball lowered into the first pail is negatively charged, what will be the charge on the electroscope leaf? Verify this.

8. *Potential.* Charge the cylindrical conductor strongly; at a distance of 1 m. place the electroscope; there will be a divergence. Move the charged cylinder nearer to the electroscope by spaces of 5 cm. each time. Note the increase of divergence (measured by the scale) on the electroscope. The *rate* of increase is not constant, it is accelerated as the cylinder approaches.

Plot the distance of the cylinder in a graph against the divergence. What result do you get?

9. Show that the potential on all points of a conductor is the same.

CHAPTER VII

ELECTROSTATICS (*cont.*)

We saw that the potential difference between two points was equal to the work done in moving unit charge from the more remote to the nearer point. When we speak of the electrical potential of a body we mean the difference between the potential of the body and that of the earth, which is taken as an arbitrary zero.

Potential can therefore be measured by the work done in moving unit charge along the potential gradient from zero (earth potential) to the surface of the charged body.

Work is measured in ergs in the centimetre-gramme-second system; it is force $\times$ distance. Unit force (1 dyne) $\times$ unit distance (1 cm.) $=$ 1 erg. The C.G.S. unit difference of potential exists between two points *when an erg of work is done in moving unit charge from one point to the other.*

Unit charge has already been defined (see p. 69). For practical requirements a much larger unit of quantity is required. It is the coulomb (named after Coulomb).

1 coulomb $= 3 \times 10^9$ electrostatic units of quantity (or charge).

On the other hand the practical unit of the electrical engineer used in measuring potential is much smaller than the C.G.S. unit (above). It is the *volt* (named after Volta).

$$1 \text{ volt} = \frac{1}{300} \text{ C.G.S. units of potential.}$$

Suppose we wished to move 1 coulomb of electricity against the potential difference of a volt, how much work must be done?

1 coulomb $= 3 \times 10^9$ units, and 1 volt $= \frac{1}{3} \times 10^{-2}$ units difference of potential.

To move a coulomb against the potential difference of 1 C.G.S. unit 3×10^9 ergs of work would be required. Against a volt potential difference:

$$3 \times 10^9 \times \tfrac{1}{3} \times 10^{-2} = 10^7 \text{ ergs.}$$

Ten million ergs are required; or, expressed in grammes weight and centimetres distance, work sufficient to raise $\frac{10^7}{981}$ gm. through 1 cm. That is, to raise 11·9 kgm. through 1 cm.

[Note that 1 dyne is the force that will produce an acceleration of 1 cm. per second per second in the mass of 1 gm. A gramme *weight* = 981 dynes.]

If the coulomb of electricity were moving from the point at higher to that at lower potential, work to the same amount would be done by it.

The voltage of the electric mains is very frequently 240. Between the electric cable carrying the supply and the earth there is a difference of potential of 240 volts, or $\frac{240}{300} = \frac{4}{5}$ of a C.G.S. unit. The work done by a coulomb in descending the 240 — 0 potential gradient would therefore be 240×10^7 ergs, which is equivalent to raising $11{\cdot}9 \times 240$ kgm. 1 cm. If the cable supplied 1 coulomb per second this amount of work would be done every second. Quite a high percentage of this energy is available for use, hence the great advantage of a cheap supply of electricity.

We have considered the potential or "electrical level" of the charge of electricity upon a conductor. It is now necessary to inquire into the distribution of the charge itself. In the first place the charge resides on the out-

side of the conductor; there is no charge within the latter. This has been proved conclusively by Faraday, who made a large cage of wire gauze, and got into it, carrying with him a very sensitive electroscope. The cage was insulated and strongly charged, until sparks began to fly across the gauze mesh. Not the slightest charge could be detected by the electroscope. There are several other ways by which this phenomenon may be tested (see Experiments, p. 92). It has its important applications. An electric safety dress of wire gauze renders the wearer safe from shock from high-tension apparatus; submarine electric cables, at points where their ends are brought to the surface, are placed, together with the attendant machinery, in iron houses.

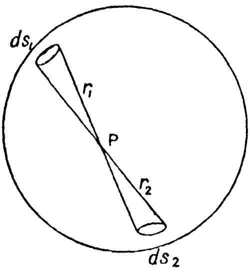


Fig 22

Since the absence of charge in the interior of a conductor has been proved, the truth of the inverse square law follows from it. Henry Cavendish established this law before 1785. At any point P inside a hollow charged spherical conductor there is no force exercised from the charge on the surface (fig. 22). The sphere may be divided into pairs of cones of small angle at their apex O with their bases equally inclined to the axis of each pair. Two such cones have bases ds_1 and ds_2. Since the charge on a sphere is uniform, the charges Q_1 and Q_2 on ds_1 and ds_2 respectively are proportional to the areas ds_1 and ds_2. The cones have the same angle at P.

$$\therefore \frac{ds_1}{ds_2} = \frac{r_1^2}{r_2^2} = \frac{Q_1}{Q_2}.$$

$$\therefore \frac{Q_1}{r_1^2} = \frac{Q_2}{r_2^2}.$$

But, since there is *no* force at P, the force on unit charge at O due to Q_1 is exactly balanced by the force due to Q_2 at O.

Therefore the forces must be inversely proportional to the squares of the distances r_1 and r_2. The same is true for any pair of cones. The intensity at P due to the charge on the sphere is zero *only if the inverse square law is true.*

The charge on a spherical conductor is spread uniformly over its surface. If we take samples of this charge from the conductor by touching it with a small copper disc mounted on a vulcanite handle (a proof plane) and transfer the samples on the disc to an electroscope, we find that an equal divergence is produced whatever portion of the conductor is touched.

This is not the case with conductors of different shapes. For example, there is an accumulation of electricity on the edges of a disc or cylindrical shaped conductor, and upon the apex of a cone. Generally speaking, we find the greater the curvature of the surface the greater the accumulation of charge. The number of units of charge per unit area is the density of the charge. If Q units are distributed over a sperical conductor of radius r, the density of its charge is $\frac{Q}{4\pi r^2}$. Since the density increases with the curvature it follows that at a point the density should be infinite. We cannot have an absolute point, but at the sharp point of a needle the density becomes very great. For a strong electric field the air becomes a conductor, so that the electric charge leaks away from a sharp point; particles of air come in contact with it, become charged, and are violently repelled, causing a " wind ". Particles of dust upon electrical apparatus will act in the same way as points and cause leakage of the charge.

In a similar manner points may act as collectors of electricity. A positively charged conductor A is placed opposite a sharp needle, mounted on a metal insulated stand (fig. 23). The charge on A *induces* on the needle a

negative charge of high density; from the needle point a stream of negatively charged air particles is repelled to A, thus neutralizing its charge. A corresponding positive charge may be collected at C.

If we substitute for A a highly electrified cloud in the

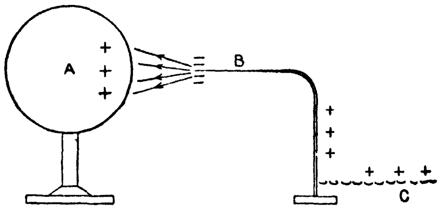


Fig. 23

air, whilst the stand B with its needle point is made to extend above the highest point of the building, its lower end being earthed, we have the lightning conductor. The cloud, instead of parting with its electricity in sudden disruptive violence, is quietly discharged by the electrified air stream produced by induction; the induced charge of the same sign as that of the cloud goes to earth.

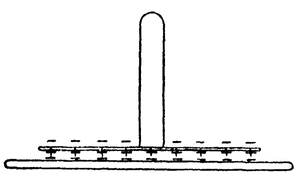


Fig. 24

Induction is employed in the various devices for obtaining electrostatic charges at a high potential. The simplest of these devices is the electrophorus (fig. 24). This consists of an ebonite or vulcanite plate, upon which rests, with few points of contact, a metal plate provided with an insulating handle. The vulcanite plate is rubbed with fur and thus negatively electrified. It is then covered with the metal plate; the charge on the vulcanite acts across the thin film of air between the plates by induction. It induces on the under side of the metal plate a positive

charge, repelling a negative charge to the upper side. If the metal plate were now lifted off and removed from the neighbourhood of the charged ebonite it would be found to be uncharged; the positive and negative charges would re-unite. But if before its removal the top of the plate is earthed by touching, the negative charge is removed, and on raising the plate the positive charge is distributed over its surface with maximum density at the edges.

Moreover, the process can be repeated a great number of times without recharging the vulcanite. We are getting electricity at a high potential in considerable quantity from one small charge. We have seen that potential connotes work; whence then comes the energy to produce this potential? It will be noticed that to lift the metal plate from the vulcanite requires more effort when the instrument is charged than when uncharged. The positive and negative charges on the metal and vulcanite attract each other; the overcoming of this attraction accounts for the extra effort. So that really the electrophorus is a device by which mechanical energy is expended in producing electric potential and separating electric charge.

If the charged metal plate of the electrophorus is brought near to a conductor, at a certain distance the resistance offered by the air to the passage of electricity will break down. At this distance the potential gradient between the charged and the uncharged body is very steep, and the *rate* of change of potential is very rapid. The dielectric is under great strain; there is a sudden disruptive discharge, and a spark passes. The energy of the charge is converted into heat and light; a minute, incandescent particle is torn off from the disc.

The spark obtained from an electrophorus is not very bright, but by applying the induction principle in the

construction of what are called influence machines it is possible to obtain an apparatus which will give long, bright sparks, accompanied by a loud snapping as the dielectric breaks down. It will be seen later that the energy for producing such discharge is stored in the dielectric; it is the latter which is under stress, not the charged conductor. To increase the dielectric strain condensers are frequently employed. We must therefore consider the action of an electric condenser.

If an earthed conductor is brought near to a charged

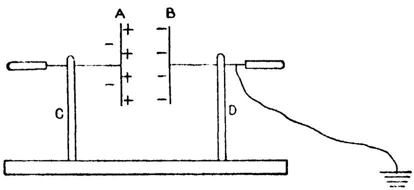


Fig. 25

electroscope there is a decrease in divergence of the leaf; for the charge on the disc of the electroscope acts across by induction upon the earthed conductor, inducing a charge of unlike sign to itself, and repelling like charge to the earth. The charge on the conductor reacts again on the disc, increasing the charge on its surface with less charge on the gold leaf; hence the decrease in divergence of the latter.

Fig. 25 will make this clearer.

A and B are two metal discs which can be moved in a horizontal direction; they are mounted on insulating pillars. A is charged positively; it acts inductively upon B, producing a negative charge on its surface and repelling to earth an equal charge of positive electricity. The charge on B now reacts upon A, inducing more positive charge upon it which, in turn, strengthens the

negative charge on B. By this means the amount of work to be done in charging A to a given potential is considerably greater when B is opposite to it. For a *given potential* the quantity of electricity that can be accommodated upon A is much greater owing to the presence of B.

The ratio of the quantity of electricity put upon a conductor to the change in potential produced by that quantity is called the *capacity* of the conductor, $C = \frac{Q}{v}$, where C is the capacity, Q the quantity of electricity, v the potential. Unit capacity is such that unit quantity produces unit change of potential. The unit of capacity is the *farad*. A condenser of one farad capacity would be raised to the potential of one volt by a charge of one coulomb of electricity. Such a condenser would be too enormous to be made; the capacity of the whole earth is only $\frac{7}{10000}$ of a farad. The micro-farad = one millionth of a farad and is the practical unit. Note that the charge of one coulomb would raise the potential of a micro-farad condenser to the potential of one million volts.

The capacity of a condenser depends upon the area of the plates and their distance apart. (In the case of a parallel plate condenser it can be proved that $C = \frac{A}{4\pi t}$, where A is the area of one of the pair of plates and t the thickness of the air space.) It also depends upon the material of the insulator between the plates, i.e. the dielectric. If between A and B in the figure above is inserted a plate of paraffin wax, whilst A is charged and connected to the electroscope, it will be found that divergence is decreased still more. The potential of A has dropped, consequently the capacity has increased. Two condensers whose areas are exactly the same, with the same distance between the plates, have air and glass respectively for their

dielectric. Obviously their capacity will not be the same; for a given charge the potential gradient in the glass will be far less steep than that in the air. The capacity of a piece of ordinary glass for inducing charges on either side of it is far greater than the capacity of a layer of air of the same thickness; it is more than eight times as much. For pure water of the same thickness it is eighty times as much.

As an illustration, suppose we have a rectangular trough made of some insulating material, the two opposite long sides of which are lined with tinfoil. Let us say that, when the box is filled with air only, it requires the quantity of 10^{-4} coulombs of electricity to raise the potential difference between the plates (one of them earthed) to 20 volts. If the box were filled with absolutely pure water for the same charge there would only be a potential difference of $\frac{1}{4}$ volt between the plates. *Eighty times* the quantity of electricity, i.e. 8×10^{-3} coulombs, could be condensed on to the metal plates before a potential difference of 20 volts was registered. It is to be observed that *pure* water is an insulator, but, owing to its solvent action, water can be obtained in an absolutely pure state only with difficulty.

Glass was used as the dielectric in the first condenser discovered by Musschenbroek (1692–1761), professor of physics in Leyden. He wished to collect some of the electric fluid (as electricity was then considered) obtained from the friction of a glass cylinder against a silk pad, and concentrate it in a glass filled with water. He led a wire into the water, holding the glass in his hand. On taking the wire out of the water whilst still holding the glass he received a severe shock.

In this case the wire and conducting water were charged from the machine. This charge, acting through the glass, induced and held bound a negative charge on the pro-

fessor's hand, and repelled to earth a positive charge. When the wire was touched the positive and bound negative charge were united through the conductor of the body, causing the shock.

Condensers, consisting of glass jars lined with metal foil within and without, were afterwards made and were called Leyden jars, as they are still.

If three precisely similar Leyden jars (fig. 26) are joined in parallel, i.e. so that all their inner coats A are connected, and likewise all their outer coats C, the latter being con-

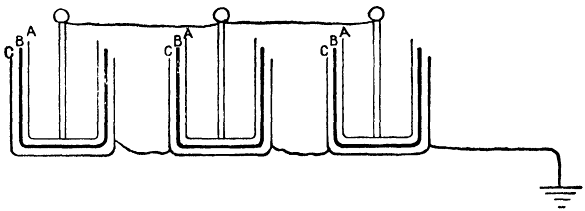


Fig. 26

nected to earth, then the capacity of the three jars is three times that of one jar—for a given potential they will accommodate three times the quantity of electricity necessary to charge one jar up to the same potential. The quantity of electricity thus stored can be large, according to the area of the coatings of the jars and the thickness. The jars are charged by connecting the knob of one to a source of positive electricity.

On connecting the inner and outer coats there is a brilliant spark and a loud cracking noise; if the potential to which the condensers are charged is high the spark can be 2 cm. long and intensely bright.

How is this spark produced? If a pair of discharging tongs is used (consisting of two limbs of brass rod hinged at the centre and provided with insulating handles) the knob of one limb of the tongs is placed in contact

with an outer coating and the other gradually brought nearer to the inner coating of one of the jars. The air between this knob and the inner coat is in a state of great mechanical strain which steadily increases, until the resistance of the air is broken down with disruptive violence, the energy which has been ended in storing up the charge of electricity is suddenly liberated—in the form of heat. The heat is so great that small quantities of the tinfoil of the coatings and the brass of the tongs are vaporised, giving the bluish white colour to the spark.

There is another extraordinary effect in the discharge. It has been proved that it oscillates backwards and forwards many times a second. On the passing of the first spark the air in the gap between the metal surfaces becomes a conductor, the positive charge, or a portion of it, surges over to the outer coating, and just as there is a recoil from a flexible steel rod when bent and released, so there is a recoil by which this charge surges back again to the inner coating, to repeat the same process many times per second. Since the air in the gap has become a conducting medium the resistance offered is small. The mathematical theory of Lord Kelvin in 1853 foretold that such an oscillation would take place. In 1858 Feddersen showed these surgings to and fro, by looking at the spark discharge of a Leyden jar in a rapidly revolving mirror; a series of flashes are seen which present a band of alternately increasing and diminishing brightness.

Further, the Leyden jar illustrates in a wonderful manner the principle of action at a distance. Its surging discharge is able to set up electric waves which can be detected miles away. These electric waves investigated by Hertz have made possible communication by wireless.

The existence of the waves can be shown at the distance of several yards, by an experiment due to Sir Oliver Lodge. Two Leyden jars, A and B, of the same capacity are fitted

with loop " aerials " each of exactly the same dimensions (two similar pieces of wire netting would answer). B has a strip of tinfoil gummed to its inner coating and reaching over the edge to within $\frac{1}{8}$ in. of the outer coating. The discharge of the jar A will produce a bright spark in B between the strip of tinfoil and the outer coating. A few trials are necessary to adjust the aerials; when the natural period of oscillation is the same for both jars the spark will be evident from one room to another.

Hitherto we have dealt with experiments which show the existence of strain in the dielectric, and not in the conductors of electricity; we have seen that the breaking down of the dielectric is attended by the evolution of energy in the form of heat and light. Electricity has been thought (by the early experimenters) to be a fluid; if so it should possess weight and for that there is no positive evidence. Since redistributions of energy occur in the case of electric discharge, electricity has been called a form of energy: is this a correct view? We cannot answer that question without considering more recent experimental evidence.

Experiments

1. To show that the electricity obtained from the electric

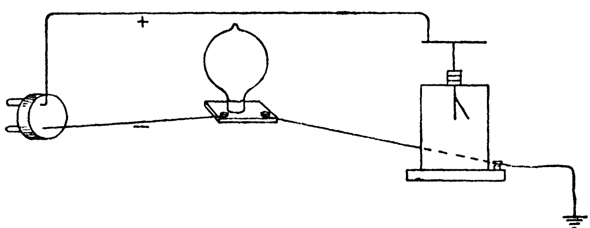


Fig. 27

mains is of the same nature as that obtained by friction (fig. 27). Connect one strand of the insulated flex attached to a wall

plug to the disc of the electroscope; the other strand to one terminal of a lamp socket *with lamp in position*. The other terminal of the socket is connected to the earthing terminal of the electroscope, which in turn is connected to earth. On switching on the current, either the lamp will light (if it is connected to the positive), when there will be no deflection of the electroscope, or there will be a deflection and no light in the lamp. Prove that the charge on the leaf is positive by bringing near a positive charge and producing increased divergence. This experiment is suitable only for direct current in the mains.

2. Faraday's experiment. Place an electroscope inside a large tin canister with small windows cut in the sides for observing the gold leaf. The lid of the canister is closed and the whole is placed on a slab of paraffin wax. There is a strong electric charge imparted to the metal box, but no divergence of the leaves is apparent.

3. Test by means of a proof plane the distribution of charge upon conductors of various shapes, each well insulated by supporting on paraffin wax. In this experiment a small cylinder of metal (a tobacco tin) is placed on the disc of the electroscope, after each charge touch the inside of the tin with the proof plane. Show that the density of the charge increases with curvature.

4. Attach a sharp-pointed needle with wax to one of the terminals of an electric machine, and show that a wind is produced when the machine is working; it is also impossible to obtain any but the shortest sparks with the needle in position.

5. Try the experiment (p. 83 above) by which electricity can be collected by means of a sharp point.

6. Test the action of the electrophorus. Scatter some fragments of elder pith on the surface of the metal plate. What happens to these fragments if the plate of the charged instrument is raised (*a*) before earthing, (*b*) after earthing?

7. The air condenser. Show how the capacity and potential alter (*a*) on moving A and B nearer together, (*b*) on placing a slab of paraffin wax between them. Test the effects by connecting A to the electroscope.

8. The Leyden jar. Show that after discharging with the tongs and waiting a few seconds a second and third spark can be obtained.

N.B.—On charging, the outer coat must always be earthed.

A Leyden jar with movable coats is required; charge the jar as usual, remove the inner coating and earth it, place the glass on an insulator after removing from the outer coat. There is no charge in either of the metal coats. Now put back the parts in their original places. A spark of undiminished brightness is obtained. This shows that the charges with their great potential difference are in the dielectric.

Arrange three jars in parallel and note the brilliance of the spark obtainable. Show that if a knitting-needle is in the discharging circuit it will possess, subsequently, magnetic properties.

Arrange jars A, B, C so that the outer coat of A is connected to the inner coat of B, and the outer of B to the inner of C. The outer coat of C is earthed, but A and B are insulated. What effect will this arrangement have upon the potential and capacity?

9. Carry out the experiment with two Leyden jars to illustrate action at a distance and the formation of a wireless wave. If you have a wireless receiving set " listening in " to a condenser discharge is worth while.

CHAPTER VIII

THE ELECTRIC CURRENT

If an insulated conductor is charged and then connected to the earth by a wire there is a flow of electricity along the wire. If the conductor is positively charged, we say that electricity flows from it to the earth. If it is negatively charged its potential is lower than the earth's, and a current is spoken of as flowing from the earth to the conductor. It is customary to state that the direction of the current is the direction in which positive electricity is moving; i.e. from higher to lower potential. We might equally well state the direction of the current by stating the direction in which a *negative* stream of electricity (electrons) would flow.

How long will the flow of electricity continue? In this respect it resembles the flow of water from a cistern; that flow will continue until the water in the cistern is the same level as the water of outflow. Electricity will likewise flow until the potential of the conductor is the same as that of the earth. The equalizing of these potentials is brought about in a very minute fraction of a second.

Now electricity *in motion* has very distinct properties, and it is by these properties that measurements of the quantity of moving electricity can be made. We have already seen that a knitting-needle through which a Leyden jar is discharged becomes magnetized, i.e. capable of attracting small pieces of iron. Moving electricity, therefore, appears to be capable of producing a magnetic effect. In order to test this further it will be necessary to have a continuous current. If this is obtained from the mains, a resistance, such as a lamp, being placed in the circuit, on separating widely the two strands of flex supplying the current it will be found that a compass needle is deflected when brought near to either strand. There must be a magnetic field surrounding each wire.

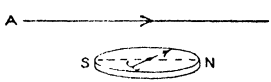


Fig. 28

Suppose the end A of the wire is attached to the terminal at the higher potential (fig. 28). Then, according to the convention mentioned above, the current is passing in the direction of the arrow, and the north pole of the compass will be deflected from its normal position N–S into the paper.

Again, if a wire carrying a strong current is passed vertically through a piece of cardboard, iron filings scattered upon the latter will arrange themselves in a series of concentric circles round the wire.

Each particle of iron becomes a tiny magnet which is attracted into a definite position.

From these experiments we learn that the magnetic field, i.e. the sphere of magnetic influence, round a current-bearing conductor is at right angles to the direction of the current. If the conductor is a straight wire this field consists of a series of circles at right angles to its length. The arrows in fig. 29 give the direction in which a north pole would be urged round the wire in the same direction as the point of a cork-screw driven into a cork.

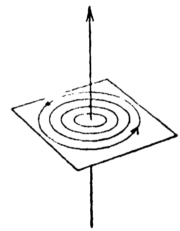


Fig. 29

Further, if a straight wire carrying a current be placed between the poles of a strong magnet, the magnetic field surrounding it will come into collision with the second field. In magnetism two like poles repel each other, consequently the wire, if free to move, will cut across the magnet's field. In fig. 30 the current I is at right angles to the plane of

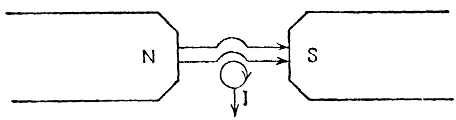


Fig. 30

the paper and travelling down into it. The wire bearing it would be repelled at right angles to NS in the direction of the arrow.

A magnetic field is an invariable attribute of the electric current. That it produces such a field was discovered by Oersted in 1820.

But what do we mean by an electric current? Is it exactly similar to a moving electric charge? To settle this question Rowland in 1876 set a plate, covered with

tinfoil sectors electrically charged, in rapid motion. He found that a magnetic needle was deflected by the moving charges just as it would have been by an electric current. So we may regard the latter as a convection current by which a charge is carried, just as hot water is carried from a boiler to a cistern by convection.

Since this moving charge gives rise to a magnetic field it must require energy to bring this about. We cannot imagine energy produced for nothing. So that in order to set a charge in motion an expenditure of energy is required.

[Recall the charge and discharge of the electrophorus; when a Wimshurst machine is working a distinct pull on the plates is felt, as an extra resistance to rotation when charged. Note carefully that in both these cases *an attraction* is being overcome.]

So that of itself, an electric charge possesses *inertia*, it behaves as though it had a definite mass. These conclusions drawn by Sir J. J. Thomson in 1881 prepared the ground for the electron theory—now no longer a theory but in the realm of fact.

Another effect by which the flow of electricity is invariably accompanied is the heating effect. The amount of heat developed is proportional to the potential of the moving charge, the current or quantity of electricity flowing per second, and the time during which the current is flowing. These facts are employed in maintaining the safety of electric lighting circuits. Fuse wires are placed at various points in the circuits so that, should the current flowing increase beyond a certain amount, the temperature rises so rapidly in these wires that their melting-point is reached and the circuit is broken.

The potential difference between the ends of a fuse wire is large, far larger than in the case of an equal length

of copper wire. Consequently the *energy expended* by the passing current is correspondingly greater; this is converted into heat, causing the melting.

In order to study these magnetic and heating effects we must devise some means of maintaining a steady potential difference, as the current obtained as above by earthing a charged conductor is far too short in duration. There are two chief ways in which this potential difference may be maintained: (1) by the energy of a chemical reaction, and (2) the movement of a conductor in the field of a magnet.

1. In 1789 Galvani of Bologna found that electric effects could be produced in animal tissue. He experimented upon the nerves and muscles of a frog's leg. He found that if two different metals, such as zinc and copper, are placed in contact, one with the muscle and the other with its corresponding nerve, then on allowing the copper and zinc themselves to touch at the same time, a convulsive kick was produced in the frog's leg. Galvani thought that the action was due to electricity in the animal tissue itself; that the galvanic shock was caused by some mysterious "electric life force".

Volta, however, proved that the electricity arose, not in the muscle and nerve, but from the contact of the two metals. If zinc and copper are brought into contact in the air zinc is positively charged and copper is negative. The charge is exceedingly small, likewise the current passing through the nerve and muscle, but it is sufficient to cause the sudden contraction.

If the zinc and copper plates are immersed in dilute sulphuric acid a new set of phenomena occur (fig. 31). When the zinc and copper are connected by a wire outside the liquid a chemical action takes place; the zinc dissolves in the acid and at the same time a current of electricity passes from the zinc through the liquid to the copper

plate, then from the copper through the wire outside and back again to the liquid. This is the direction of the flow of positive electricity which (according to convention) indicates the current direction. A compass needle, placed beneath the outside wire, is deflected; the temperature of the wire rises, the evidence of the current is complete. If we put into the circuit an ammeter to measure the current we find that after a time the latter decreases until it becomes zero. At the same time bubbles of hydrogen gas are formed upon the copper. When these bubbles are detached the current is renewed.

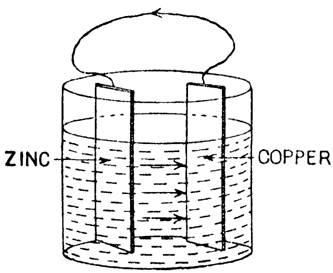


Fig. 31

What is the cause of this flow of electricity? In order that it may take place the copper plate must be at a higher potential than the zinc. Again, there is a flow of electricity from some point *very near to the zinc plate* through the liquid to the copper; so that the potential at this point must be higher than that of the copper.

The full theory of the action cannot be dealt with here. It is enough to say that the zinc is acted upon by the acid, and this chemical energy is stored in potential electrical energy in a very thin film of liquid surrounding the zinc plate. As the current passes through the conducting acid and wire there is a gradual fall in potential, back again to zero at the zinc plate. The potential slopes are shown in fig. 32; the heights of the lines E′A, G′C represent the potentials. The zinc is at negative potential but the film of acid around it rises to positive potential A. There is a fall through the liquid to B, and from B to C, i.e. from the surface of the film around the copper plate to the plate itself; then there is a fall CD along the wire, back again to the potential of the zinc. Note that in the case of an electrostatic charge the potential at all

points of a conductor is the same; this is not the case with a current of electricity.

The potential difference between the copper and zinc plate (which is represented by G′C) may be regarded as the pressure at which the current is driven through the wire. The total pressure of which the cell is capable is called its *electromotive force.* It is measured in volts, and

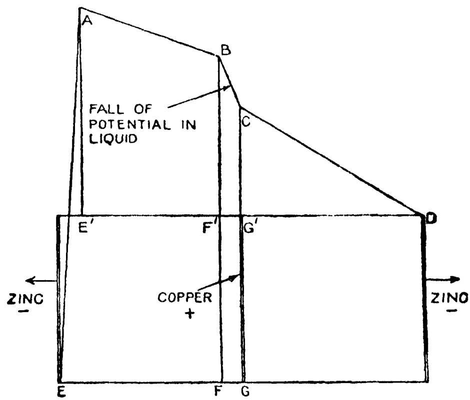


Fig. 32

is made up of (*a*) the number of volts used up in driving the current through the interior of the cell, (*b*) the potential difference between the ends of the wire. In order to keep a steady current in the cell the hydrogen on the copper plate must be got rid of. It causes a current to flow in the opposite direction; this current gradually neutralizes the original current.

The making of electric batteries resolves itself into eliminating this unwanted hydrogen. This can be done by oxidizing it to form water, as in the bichromate cell; by absorbing it first and then slowly oxidizing it as in the Leclanché cell and dry cell (see experiments).

Accumulators or secondary cells are now very widely

used. They consist of heavy lead gratings in a strong solution of sulphuric acid. On passing a current through, lead dioxide is formed at the plate attached to the positive, whilst hydrogen escapes at the negative plate. The energy of the charging current is used up as chemical energy to produce the lead dioxide. On discharge this lead dioxide is decomposed by liberated hydrogen, the energy of the chemical reaction is again available to supply the current.

2. The production of a current in a conductor by moving it near a magnet, or by varying the strength of the magnetic field in any way, was discovered by Faraday in 1831, who thus connected the phenomena of electricity and motion. He showed that when a magnet is approaching a closed conductor, such as a coil of wire with its ends attached to an ammeter, a current of electricity is produced in the coil. If the north pole of the magnet is approaching the coil in the direction of the axis then the induced current will be anti-clockwise. If we have a coil of wire wound on an iron core which is rotated between the poles of a magnet, a current will be induced whose direction is reversed twice every revolution.[1] By suitable means a current travelling in *one* direction can be obtained from this rotating coil. Upon this principle the modern dynamo is constructed.

By these discoveries of Faraday it became evident that an electric current was always accompanied by a magnetic field, and that a magnetic field, whenever it varied in intensity, produced an electric current in any conductor within its influence.

N.B.—By a magnetic field we mean the region round any magnet throughout which its influence is felt.

We must now consider what is the connexion between

[1] As the one half of coil recedes from the north and approaches south pole current is clockwise; as it approaches the north current is counter-clockwise.

difference of potential and the quantity of electricity passing through a conductor per unit time. Henry Cavendish (1731–1810) carried out experiments upon the resistance to the passage of electricity of rain-water and of iron. This he did by means of a Leyden jar and his own body. He compared the shocks he got by discharging the jar through various conductors, his body being part of the circuit. He altered the lengths of the conductors until the shocks were judged to be equal. His results were extraordinarily accurate. He showed further, by means of an electroscope, that the momentary electric current produced by the discharge of a condenser was proportional to the potential difference between its plates.

It was G. S. Ohm, a Bavarian physicist, who first stated the relationship between potential difference and current. *For a given conductor, the potential difference between its ends divided by the current flowing in it gives a constant quantity.* Ohm had no means of establishing the law with any great certainty. Like Dalton's atomic theory it was obtained deductively, though it has been verified with a high degree of accuracy by subsequent experiments.

$$\frac{\text{Potential difference}}{\text{Current}} = \text{a constant.}$$

For this to hold the conductor must remain under constant conditions; e.g. its temperature must not vary. This constant is called the resistance of the conductor. Again,

$$\frac{E}{c} = R;$$

$$E = \text{potential difference}, \; c = \text{current}, \; R = \text{resistance};$$

$$\therefore \frac{c}{E} = \frac{1}{R}.$$

The reciprocal of R is called the conductance. The conductance may therefore be defined as the current passing

through a conductor for a unit potential difference between its ends.

We are now in a position to define the units which are used in the measurement of the electric current. We have already seen that the latter consists of a moving charge of electricity, just as a stream consists of moving particles of water. A flow of water in a pipe of uniform cross section and an electric current resemble each other in the following respects:

1. Flow of water is proportional to the difference of pressure between the ends of the pipe.

   Current is proportional to the difference to the potential between the ends of the conductor.

2. The fall of pressure along the pipe is uniform and proportional to its length.

   Fall of potential along the conductor (of uniform cross section) is uniform and proportional to the length.

3. Amount of work done per second by the water in overcoming the friction of the walls and converted into heat is proportional to the quantity flowing per second multiplied by the difference in pressure.

   Amount of work done by the current in overcoming resistance of conductor and converted into heat per second is proportional to the potential difference times the quantity of electricity flowing per second.

There is another property of the current which has no analogy in the flow of water. That is, the strength of the magnetic field set up outside the current and at right angles to its direction is proportional to the quantity of electricity flowing per second. This has been definitely established by experiment and affords a basis for determining a unit of current.

Imagine a current flowing in the arc AB of a circle ABD, whose radius AC = 1 cm. Let AB = 1 cm. (fig. 33). Then if the magnetic field due to the current in AB repels unit magnetic north pole with the force of 1 dyne, unit current flows through AB. (Note, the same current in the complete circle would cause a repulsion of unit pole of 2π dynes.)

The unit of current in common use is derived from this and is $\frac{1}{10}$ of its value; it is called the *ampere*. If we were able to take up a position in a conductor in which an ampere of current is flowing, and watch the electricity go by, a *coulomb* of electricity would pass us in 1 sec. If an electromagnetic unit of current were flowing, 10 coulombs would pass per second. Suppose in this conductor the potential difference between its ends were increased ten times, ten times the quantity of electricity would pass by in 1 sec. The current would be increased to 10, or a 100, coulombs, according to the strength of the original current.

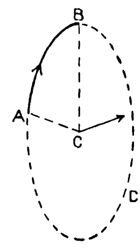


Fig. 33

We have already seen that the volt is the unit of potential difference (or of electromotive force) and that it is $\frac{1}{300}$ of a C.G.S. unit.

A conductor through which an ampere is passing when the potential difference between its ends is 1 volt, is said to have the resistance of 1 *ohm*. This is the Board of Trade unit of resistance; it is equivalent to the resistance offered by a column of mercury 106·3 cm. long and having a cross section of 1 sq. mm., the temperature being 0° C.

The instrument by which the strengths of electric currents are compared and measured is called a galvanometer. There are two chief types of instrument: (1) Those in which the current flows in a fixed coil of wire

and causes the deflection of a compass needle placed at the centre of the coil. (2) Those in which the coil is suspended between the poles of a fixed magnet; when the current flows through the coil it produces a deflection of it through a given angle which can be measured.

In the first type it is usually the tangent of the angle of deflection which is proportional to the strength of the current, the plane of the coil being placed in the magnetic meridian. The tangent galvanometer (fig. 34) consists of a brass box A which contains a short magnetic needle B balanced on a pivot; a light aluminium pointer is fixed at right angles to this, and passes over a circular scale C. The ring D, in a vertical plane, can be rotated round its own axis on the movable base E. Turns of wire are wound round D and have their ends fixed in the terminals F, F. The needle B comes to rest when no current is flowing in the magnetic meridian. Box A is adjusted so that the pointer C is on the zero of the scale. The ring D is rotated until the coils of wire are in the magnetic meridian and parallel to the needle B. After levelling the galvanometer is ready for use. A current is passed to the terminals on the left, by which two coils of wire are included in the circuit. The tangent of the angle of deflection is proportional to the current.

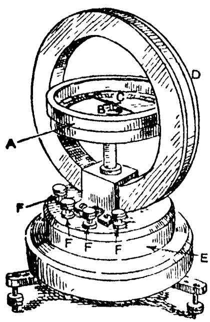


Fig. 34

$$C = \kappa \tan\theta,$$

where κ is a constant depending upon the apparatus and the strength of the earth's magnetic field.

Let A and B represent cross sections of the ring D containing the wires (fig. 35). A current coming up through

the paper at A and passing down into it at B would produce a magnetic field at right angles. It would repel unit north pole at N in the direction NF.

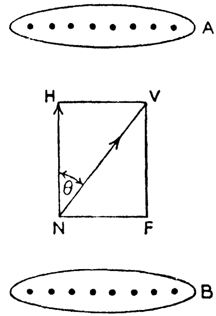


Fig. 35

It is almost impossible to measure directly this force acting on N.

We can, however, compare it with the force due to the earth's magnetism.

If NF represents force due to current upon N in magnitude and direction, and if NH similarly represents the force due to the earth's field (at right angles to NF), the *resultant* is represented by NV.

$$\frac{NF}{NH} = \tan HNV = \tan\theta.$$

$$\therefore \frac{F}{H} = \tan\theta; \text{ and } F = H\tan\theta,$$

where F and H are the magnetic forces due to the current and earth respectively.

The same reasoning applies to the south pole of the magnetic needle.

We saw that in the case of an electromagnetic unit of current flowing through a circle of unit radius the force acting upon unit north pole $= 2\pi$ dynes. The force is inversely proportional to the square of the distance of the wire from the centre.

$$F = \frac{2\pi r}{r^2} = \frac{2\pi}{r}.$$

If there are n turns of wire and the current has a value of i amperes.

$$F = \frac{2\pi n i}{10r} \text{ (as an ampere is } \tfrac{1}{10} \text{ of an electromagnetic unit),}$$

$$\therefore F = \frac{2\pi n i}{10r} = H\tan\theta; \ \therefore i = \frac{10Hr}{2\pi n}\tan\theta.$$

The fraction $\frac{10Hr}{2\pi n}$ is the *reduction factor* of the galvano-

meter. If we know its value we can find the actual current in amperes.

Instruments for measuring current in amperes directly usually consist of a moving coil supported between the poles of a strong magnet. When a current is passed through this coil the magnetic field which it sets up reacts upon the field of the permanent magnet and causes a movement of the coil. In fig. 36 the coil C rotates about its axis against the tension of two spiral springs, one of which is shown at B. A pointer moves over a scale not shown in figure, which gives the current value directly. A is a cylinder made of soft iron so that the field due to the poles N and S may be uniform for all positions of the coil.

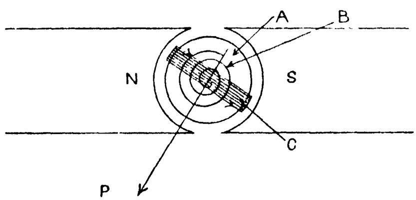


Fig. 36

If the current is passing from the back of the paper to the front and in the direction of the arrows the coil will move so that the pointer advances from left to right.

Knowing the values of the currents produced by any source of electricity we can proceed to the measurement of E.M.F. For, by Ohm's law,

$$c = \frac{E}{R}.$$

Now the resistance R is made up of the resistance of the external circuit r_1, and of the internal resistance of the generating source r_2.

$$\therefore c = \frac{E}{r_1 + r_2}.$$

If we make r_1 very large in comparison to r_2, for two

currents c_1 and c_2 from two different sources, we can write

$$c_1 = \frac{E_1}{r_1 + a},$$

and, keeping the same external resistance,

$$c_2 = \frac{E_2}{r_1 + b},$$

where a and b are the internal resistances. Since r_1 is very large compared to a and b,

$$\frac{c_1}{c_2} = \frac{\frac{E_1}{r_1 + a}}{\frac{E_2}{r_1 + b}} = \frac{E_1}{E_2}.$$

An apparatus for measuring E.M.F. is called a voltmeter. Its structure is similar to that of an ammeter, excepting that a resistance is added to it, the current first passing through the resistance and then through the instrument. The readings on the scale are calibrated by means of an E.M.F. of known value.

The heating effect of the current is sometimes used in its measurement. This is the case in the hot-wire ammeter, in which part of the current heats a platinum-iridium wire. The expansion of this wire causes the movement of a pointer over a scale. The amount of heat developed is proportional (as shown by experiment) to the E.M.F. multiplied by the current and the time in seconds. $Ect \propto H$. But $E = Rc$ (Ohm's law); therefore $c^2Rt \propto H$, so that for a given resistance the heat developed per unit of time is proportional to the square of the current.

All these properties of the electric current which we have considered point in a very definite direction. We

have seen that the electric current is completely represented by a quantity—a charge—borne along in a convection current, that during this motion there is an expenditure of energy appearing as a magnetic field; that the passage of electricity through a conductor is attended by the evolution of heat, and that the quantity produced of this heat is proportional to the square of the current. In view of all these facts it is impossible to separate the idea of mass from an electric charge. If mass, i.e. quantity of matter, and charge are so closely connected, can it be that just as there are atoms of matter there are atoms of electricity?

Experiments

1. Charge a large conductor, such as a metal bucket placed upon a slab of paraffin wax, by means of an electrophorus and with a positive charge. Connect the positive terminal of a sensitive ammeter to the conductor by insulated wire, the other terminal being earthed. Is there any current detectable?

2. Try the effect of the magnetic field due to the current from the mains upon a compass needle. Note that " to a man swimming in the current and facing the needle the north is always deflected to the *left* " (Ampère's rule). Show that the deflection is approximately double for two wires, or for a complete loop of wire round the needle.

N.B.—Direct current only from the mains can be used for this experiment.

3. Pass a strong current (direct current) through a wire pushed through cardboard. Show with iron filings from a sieve how the magnetic field is distributed.

4 Try experiment on p. 95. The straight wire passes vertically into a small vessel containing mercury (at I in fig. 37). It is hinged at the top. On completing circuit repulsion takes place, breaking the circuit, which is again made as the wire swings back.

5. Put up a simple cell (consisting of zinc and copper plates in dilute sulphuric acid). Test the current you obtain with

an ammeter, and show how it decreases as the bubbles of gas on the copper plate appear.

The zinc plate should be rubbed over with mercury before use.

Try the effect of adding a solution of potassium bichromate; does this prevent polarization? What happens to the colour of the solution?

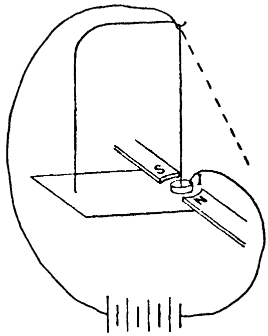


Fig. 37

6. Examine a Leclanché and a Daniell cell, and note how polarization is prevented in them.

7. Bring up to a coil of wire (an inductance coil as used for wireless reception and mounted in its holder will do very well) the north pole of a bar magnet. The ends of the coil are connected to a sensitive ammeter or galvanometer. Note what takes place as the north pole advances towards and passes through the coil. Show that the current is anti-clockwise when the magnetic field is increasing (the centre of the field from which lines of force radiate out is the north pole of the magnet).

8. Place two coils side by side, one of which is connected to galvanometer as before. Through the other a current may be passed, the circuit being broken by a key. Note what happens on starting and stopping, increasing and decreasing the current. What is the direction of the current induced in the second coil in each case? Note that it is the development of the magnetic field due to the current in first coil which produces an *opposing field* in the second, and consequently a current the reverse of that in the first coil—*on starting*. What happens on stopping?

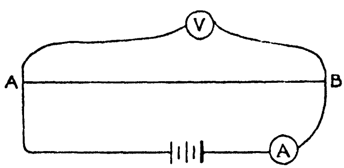


Fig. 38

9. Demonstration of Ohm's Law (fig. 38). A German-silver wire AB 1 m. in length is attached on a board at A and B (a metre bridge). A voltmeter V is placed in circuit in parallel,

and an ammeter and an accumulator cell in series. Divide the voltmeter reading by the ammeter reading, increase the voltage by adding another cell in series and again divide. This can be repeated several times, if AB has a high resistance, without it becoming heated. The quotient obtained in each case is the same.

10. Pass a current from a single Daniell cell through a tangent galvanometer—a resistance being in the circuit of about 10 ohms. Repeat, using two cells. Is the tan of the angle of deflection in the second case twice that in the first?

11. Examine the construction of a voltmeter and an ammeter and note their points of resemblance and difference. Compare the E.M.F. of a Daniell cell and of a Leclanché cell, using a sensitive galvanometer and a high resistance. For the latter two pieces of tin-foil are gummed on to a piece of ground glass (about 2 in. square), and a pencil line is drawn between them.

CHAPTER IX

ELECTROLYSIS, IONIZATION. DISCHARGE OF ELECTRICITY IN A PARTIAL VACUUM. THE ELECTRON.

If we pass an electric current through a liquid such as a solution of salt in water, an entirely different set of phenomena occur from those shown in the passage through a conductor such as a metal wire. Let a current of 8 volts E.M.F. be passed through the salt solution by means of platinum plates, called electrodes, which convey the current into and out of the liquid. It will be found that at the point where the current enters the liquid a gas will be given off; at the electrode by which the current leaves the liquid there will be a deposit which will darken the platinum plate. The solution near to this point of exit, the *cathode*, will become alkaline, whilst the gas given off at the point of entry (the *anode*) will have the

irritating smell of chlorine and will bleach a coloured piece of cotton.

If instead of the brine we use solutions of different metallic salts we shall get deposited at the cathode a coating of the metal upon the platinum; at the anode evolution of a gas.

Faraday investigated the flow of electricity through a solution of an acid, or of a metallic salt—which is called *electrolysis*—and showed that such a flow is always accompanied by chemical decomposition of the solution, or *electrolyte*. He also proved the truth of the following:

The amount of chemical action at all points of the circuit is the same.

The amount of metal or gas liberated at the electrodes is proportional to the strength of the current.

If the current is passed through several electrolytes in series, e.g. through copper sulphate, silver nitrate, sulphuric acid (a dilute solution), lead nitrate, the weights of the deposit at the cathode in each case bear a definite ratio to each other—they are proportional to the *chemical equivalents* of the substances.

For example, if the above electrolytes were chosen, for every 1 gm. of hydrogen liberated there would be: 31·78 gm. of copper; 107·9 gm. of silver; 103·6 gm. of lead. This is equally true for the substances liberated at the anode. Here the ratio of the masses is that of the chemical equivalent. But since the substances at the anode are more complex, it is usual to estimate the masses at the cathode.

That weight of an element which will combine with or displace 1 gm. of hydrogen is called *its equivalent*. The number of atoms of hydrogen with which 1 atom of an element will combine is called its *valency*. The equivalent of copper is 31·78, but its atomic weight is 63·56; so that one atom of copper displaces two atoms of hydrogen. Therefore half the atomic weight in grammes is the equivalent of copper.

If we can find the weight of silver deposited by a given quantity of electricity, e.g. a coulomb, we can obtain the weight of *any other element* deposited by the same quantity, if we know the chemical equivalent of the element.

The weight of an element deposited by electrolysis by a coulomb or, what is the same thing, the current of an ampere in one second is called the *electro-chemical equivalent*.

For silver it is 0·001118 gm., for copper, 0·0003295.

How many coulombs then will be required to deposit 1 gm. of hydrogen, 107·88 gm. of silver, or 31·78 gm. of copper?

For silver the calculation is $\dfrac{107{\cdot}88}{111{\cdot}83 \times 10^{-5}} = 96{,}470.$

No matter what the element may be, 96,470 coulombs are required to deposit by electrolysis its *equivalent weight in grammes*.

If we divide this number of coulombs by the number of atoms present in 107·88 gm. of silver, we shall get the amount of electricity used in depositing one atom. Now we have seen that the number of molecules contained in the molecular weight in grammes is given by the Avogadro constant, $68{\cdot}2 \times 10^{22}$ (see Chapter III). Now each molecule of the silver salt will give one atom of silver.

$$\therefore \text{ Charge required for each atom } = \frac{96{,}470}{68{\cdot}2 \times 10^{22}} \text{ coulombs}$$

$$= \frac{96{,}470}{68{\cdot}2 \times 10^{22}} \times 3 \times 10^{9} = 4{\cdot}3 \times 10^{-10} \text{ electrostatic units.}$$

We can now build up an hypothesis to account for the phenomena during the passage of a current through an electrolyte. The salt in solution decomposes into two portions; one is positively charged, the other possesses an

equal negative charge. These portions owing to their charge are attracted to the electrodes and move through the electrolyte; for this reason they are called *ions*. The positive ion (the metallic ion in the solution of the salt of a metal) is attracted to the cathode (—), whilst the non-metallic element or group of elements being negatively charged passes over to the anode.

The question arises, are these ions already existent in the solution before the current is applied, or is their formation by the separation of the molecules of the electrolyte due to the electric current? To decompose a stable substance such as sodium chloride requires a considerable expenditure of energy, yet we find, however small the electromotive force of the applied current, *some* flow of electricity will take place. This points to the existence of some free charged particles.

Further, we should expect that a solution A of copper sulphate of half the strength of B would have half its conducting power, as the number of ions in A would be half that in B. This is not the case, for on diluting B to A strength many more fresh ions are produced, so that the conductivity of A is more than half that of B.

The ionization theory was developed by Arrhenius; according to it the conductivity of a solution is proportional to the number of free ions present.

It is difficult to see how a metal like sodium, which is kept in oil to prevent the action of the moisture and oxygen of the air upon it, can exist as an ion and travel through a solution to its destruction at the cathode. The sodium ion possesses a charge, its nature is therefore quite altered; on giving up that charge at the cathode, it becomes an uncharged speck of the well-known metal and acts upon the water surrounding it.

There is much supporting evidence to the ionic theory; the rate of transport of the positively and negatively charged

ions is not the same (see experiments). This can be shown by the alteration in density of the electrolyte. The charge associated with each atom is always a fixed amount ($4 \cdot 3 \times 10^{-10}$ electrostatic units), or a multiple of this; for a divalent element it is twice that amount, for a trivalent element three times, &c. It is never less than the fixed unit.

Does this imply the existence of an atom of electricity? We must consider the evidence from an entirely new field of inquiry.

If two conductors placed near to each other in air are charged until the potential difference between them becomes very high, the resistance offered by the air will be broken down with sudden violence and a spark will pass from one to the other. The length of the spark, i.e. the thickness of the layer of air between the conductors, depends on the potential to which the latter are charged, their shape, and the pressure of the air between them. Moreover, the passage of the first spark makes the passage of others an easier matter, and illumination of the negatively charged conductor facilitates the passage of the spark. The reason for these facts will appear later.

If the discharge takes place between terminals contained in a vessel from which the air can be exhausted, many remarkable phenomena occur.

The arrangement of the apparatus is that given in the photograph (fig. 39). The terminals of an induction coil are attached to a vessel from which the air can be exhausted by an air-pump on the right. Two metal terminals are placed in this globe, one of which can be moved so as to increase the distance through which the discharge can travel.

Before exhausting the globe, the spark passes between the terminals of the coil, seen immediately behind it. When the air pressure has been reduced (down to about

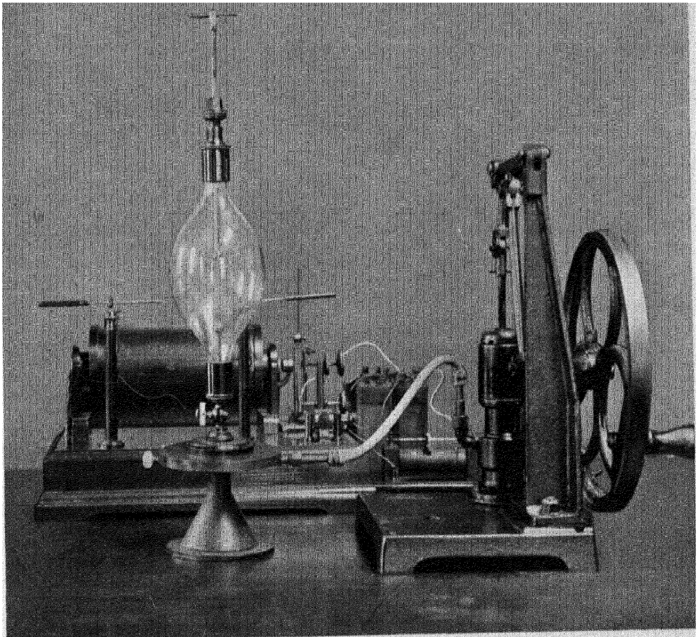


Fig. 39.—Apparatus for electric discharge in a partial vacuum

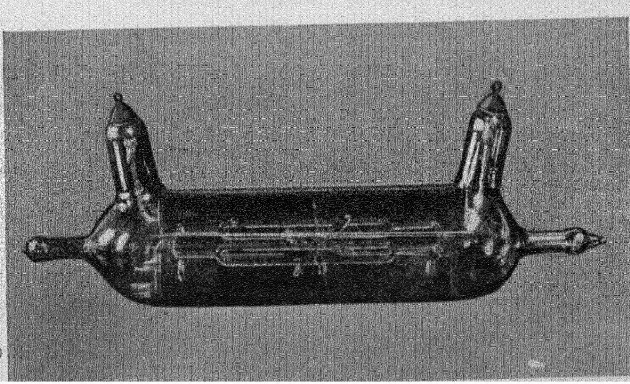


Fig. 40. Tube to show mechanical action of cathode rays

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2 cm. of mercury), the spark between these terminals ceases, and a crimson stream appears between the terminals in the globe. If the pressure is further reduced, the luminous column is still apparent but does not reach the cathode, at which there appears to be an empty space, the cathode glowing luminously. The spark gap between the terminals of the coil may be reduced to a fraction of an inch without any spark passing; the resistance in the globe has become very small.

With further reduction of pressure the crimson colour disappears, and the column, called the positive column, appears to be divided up into little luminous discs with convex sides towards the anode.[1] Beyond this reduction of pressure it is very difficult to maintain the exhaustion of the globe with the apparatus shown. It is better to use long glass tubes with aluminium terminals at either end which have been sealed under exhaustion with a mercury pump. The following are the successive stages with decreasing air pressure in the tubes:

1. The luminous discs become larger, the empty space near the cathode (called the *Faraday dark space*) is less distinct. The luminous glow separates from the cathode; between the cathode and this glow is a dark space—*Crookes' dark space.*

2. The glow disappears and the tube is apparently empty. Crookes' dark space occupies the whole of it. The boundary of this dark space is always luminous; if it extends to the glass walls of the tube these give out a bright yellow-green light (for soda glass).

In this dark space something apparently is emitted from the cathode which travels in straight lines across the tube to the anode, and even beyond that to the glass sides. This was the view held by Sir William Crookes who

[1] This is well seen in Geissler tubes.

investigated the rays. There is evidence that actual minute particles are hurled across from the cathode.

1. If an obstacle is put in their path a dark shadow of its shape is produced on the wall of a tube, its outline appears to be stencilled there.

2. There is a mechanical force exerted upon the body. Fig. 40 illustrates a tube in which is placed a little mica wheel running on rails. By the bombardment of the cathode rays this wheel can be turned and moved up a slight incline. Sir J. J. Thomson has shown that the effect is partly mechanical and partly that of the radiometer.

3. Heat is produced by the rays; if the cathode is concave these rays can be brought to a point at which the heat produced will melt platinum.

In 1893 Lenard showed that the rays would pass through a thin aluminium window let into the end of the tube. He considered that they could not consist of actual particles, if they were they would be stopped by the aluminium. He thought, therefore, that they were waves resembling light waves.

If a magnet is placed over the tube in which the rays are passing, it will cause a deflection of this cathode stream, just as we saw would be the effect upon a conductor bearing a current if free to move. In fig. 41 the fluorescence in the tube is shown heaped up to one side; the rays have been attracted to the side of the tube by a magnet. The latter is not shown; its north pole was immediately above the tube.

If two plates are kept at a great difference of potential the cathode rays if made to pass between them are deflected; the direction in which they are deflected is at right angles to the direction in which a magnet will deflect them. In fig. 42 is represented a cathode tube, one of the wires to the terminals of which is wound

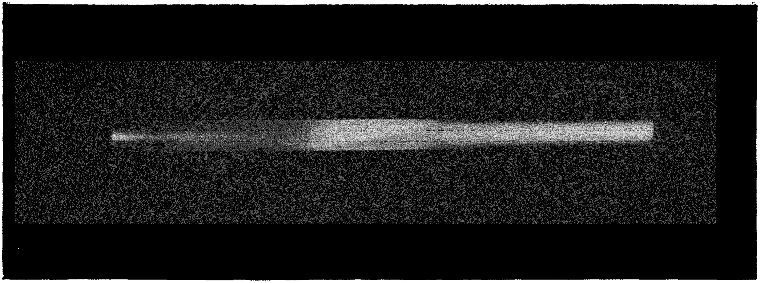

Fig. 41.—Cathode rays attracted by a magnet

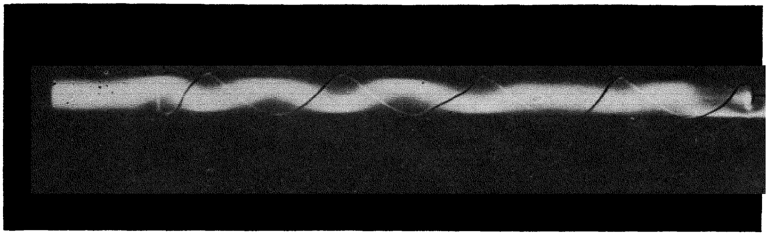

Fig. 42.—Cathode rays under a spiral electrostatic field

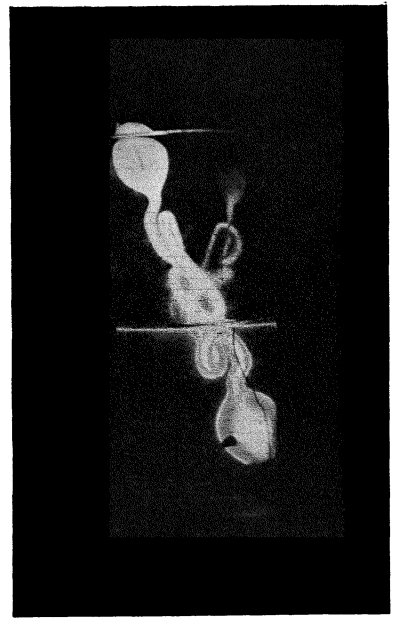

Fig. 46.—Geissler tube fluorescing in a solution of quinine sulphate

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spirally round it. The potential difference between this wire and the cathode stream is very high, consequently the stream is seen deflected spirally at right angles to the spirals of the wire.

It was shown by Perrin that the cathode rays gave a strong negative charge. The cathode K (fig. 43) gives off a beam of rays which pass into the metal cup B, which is connected with an electroscope. The latter is rapidly charged negatively. If now A is made the cathode, B will acquire a positive charge, and K a negative. It was shown further that the cathode rays even when passed through aluminium still retained their negative charge.

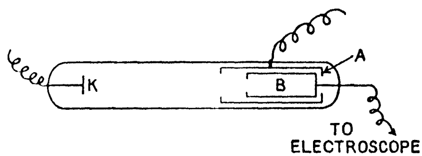


Fig. 43

There is, therefore, reason for regarding cathode rays as a stream of negatively charged particles projected with great velocity. If this is the case it should be possible to determine (1) their mass, (2) their charge, and (3) their velocity.

If e is the charge of each particle and v its velocity the current it produces has strength ev.

If we apply a magnetic field H at right angles to its direction of motion its path will become circular. Its acceleration will be $\frac{v^2}{r}$, where v is its velocity, and r the radius of the circular path. If m is the mass of the body the force upon it in its circular path $= \frac{mv^2}{r}$, which is equal to the product of the magnetic field and current.

$$\therefore \mathrm{H}ev = \frac{mv^2}{r}, \text{ i.e. } \frac{mv}{e} = \mathrm{H}r \ldots\ldots\ldots\ldots (1).$$

We have seen that an electrostatic field produced by a high potential difference will deflect the cathode rays. By putting the magnetic field at right angles to the electrostatic field the two can be adjusted so that they neutralize each other, and the rays will pass undeviated.

If V is the voltage of the field, the force on a particle will be $e\mathrm{V}$,

$$\therefore e\mathrm{V} = \mathrm{H}ev \text{ (see above).}$$

$$\therefore \frac{\mathrm{V}}{\mathrm{H}} = v. \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

From (1) $\frac{mv}{e} = \mathrm{H}r$,

$$\therefore \frac{m}{e} = \frac{\mathrm{H}r}{v} = \frac{\mathrm{H}^2 r}{\mathrm{V}}; \text{ and } \frac{e}{m} = \frac{\mathrm{V}}{\mathrm{H}^2 r}.$$

In this manner it was established by Sir J. J. Thomson that the ratio $\frac{e}{m}$ (approximately $1{\cdot}77 \times 10^7$) was the *same for all* cathode rays, no matter what the metal of the terminals may be between which the discharge is passing. This same ratio has been obtained by other methods and found in every case the same; it is independent of all circumstances.

When the cathode discharge takes place, we may therefore picture minute particles torn off from the cathode, whose mass is $\frac{1}{1800}$ of that of hydrogen, and hurled with the velocity of 50,000 or more kilometres per second across to the anode. No matter what the material of which the electrodes are made, the same particles are flung off in every case. If they can be produced from any kind of material they must be an essential portion of all atoms. They do not part with their negative charge on passing through metals such as aluminium. There is no doubt that they constitute atoms of elec-

tricity. They are called *electrons*; an electron cannot be separated from its negative charge, the charge constitutes the electron.

Experiments

1. Electrolyse a weak solution of sulphuric acid in a Hoffmann apparatus shown in fig. 44. The current from the mains (if D.C.) can be used with a lamp resistance in the circuit. Note that the gas given off at the cathode has twice the volume of that at the anode. On opening the taps the pressure of liquid in central tube forces out the gas. The gas at the cathode burns, whilst that at the anode (oxygen) will relight a glowing piece of string.

2. Pass from a 4-volt accumulator a current which flows in series through (*a*) a solution of copper sulphate (the current being led in by copper plates); (*b*) a solution of lead nitrate (through lead plates); (*c*) a solution of silver nitrate (through two plates of silver foil).

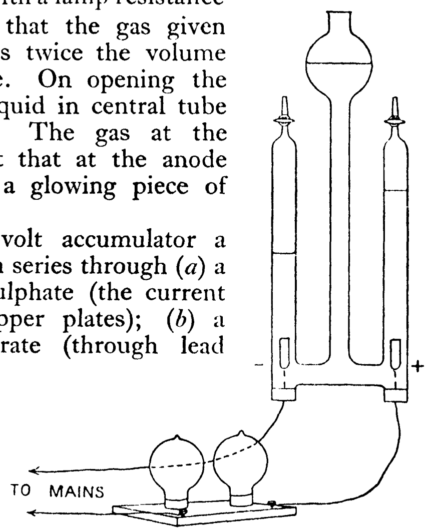


Fig. 44

After the current has passed for ten minutes take out the silver cathode and dry and weigh it. Replace this cathode and pass the current for another ten minutes. Weigh all the cathodes after drying them and note that all have gained in weight. You will find that the quantity of silver deposited has doubled since weighing after the first ten minutes.

What is the ratio of the *gain* in weight in each case? If the equivalent of silver is 107·88, find the equivalents of lead and copper.

N.B.—The accumulator should be fully charged before use. It is assumed that the rate of delivery of the current is constant throughout the experiment; this will be the case if

not more than an ampere of current is used. The area of the plates of the different metals immersed in the liquids should be about 10 sq. cm. each.

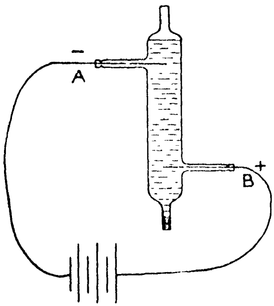


Fig. 45

3. Fill the outer jacket of a condenser with a 10 per cent solution of copper sulphate (fig. 45). Fix into each of the side tubes A, B, stout copper wires connected to an accumulator, the top wire being the cathode. Note the changes taking place in the concentration of the liquid. The region round the cathode becomes much lighter in colour. The speed of the SO_4 ions is greater than those of the copper.

The experiments with the induction coil are lecture experiments; they should not be attempted by pupils alone. A 6-in. spark coil run from an 8-volt accumulator gives good results, though a smaller coil would give sufficient potential. Geissler tubes to show the striations in the tube on further exhaustion can be obtained readily.

CHAPTER X

X-RAYS; IONIZATION OF GASES

We saw in the last chapter that, according to the ionic theory, each ion of hydrogen carried a definite charge upon it; the ratio of this charge to the mass of the hydrogen ion is 96,470 coulombs per gramme, that is 9647 electromagnetic units per gramme. But, in the case of the electron $\frac{e}{m}$ has been found to be $1{\cdot}77 \times 10^7$ electromagnetic units per gramme. So that the ratio $\frac{e}{m}$

is approximately 1830 times greater for an electron than for a hydrogen ion.

We are accordingly driven to the conclusion that either (1) the charge on the electron is 1830 times as great as the charge on the hydrogen ion, or (2) the mass of the electron is $\frac{1}{1830}$ of the mass of the hydrogen ion, i.e. a hydrogen atom. When these phenomena of the cathode rays were first investigated it seemed revolutionary to believe in the existence of a particle whose mass was nearly two thousand times less than that of a hydrogen atom. Further experiment was necessary, and a determination of the mass and the charge of the electron separately, not merely their ratio. In order to follow this work we must take up again the examination of the cathode rays.

In addition to the phenomena already mentioned, there is a fluorescence in the tube. Further, when the current is switched off, if the tube is in a dark room, a faint glow can be seen persisting for several seconds, the tube walls phosphoresce.

Fluorescence is brought about by the absorption of light. When this happens, as a rule, the energy so obtained is converted into heat. If, however, the wavelength of the light absorbed is very short, the latter gives rise to new light waves which are well within the visible spectrum. For example, ultra-violet light is invisible to our eyes, but if it falls upon a solution of quinine sulphate fluorescence takes place, and the quinine glows with a brilliant blue light. The photograph shows a small Geissler tube (fig. 46, see plate facing p. 116) through which a discharge is passing. The tube is immersed in quinine sulphate, and round its surface is a bright fluorescent border. When fluorescence occurs the wavelength of the light is usually lengthened and seldom

decreased. So that the wave-length of the light produced inside the tube *before* being altered by fluorescence must have been short. There is a selective absorption of waves of particular length, and the vibrating particles which produce the light are electrons.

It was whilst carrying out experiments upon fluorescence that Röntgen found that a fluorescent substance (such as zinc sulphide or barium platinocyanide) glowed when brought near to a cathode tube. He showed that the rays produced by the cathode stream at the walls of the tube would pass through ordinary matter, and would act upon a photographic plate. These rays, discovered in 1895, he called X-rays owing to the uncertainty of their origin. They are produced only when the cathode stream of electrons strikes an obstacle, no matter what the obstacle may be. They travel out from the surface of the obstacle in all directions and in straight lines. When the rays pass through the glass of the tube they produce a yellow-green fluorescence at its surface. They penetrate opaque objects. The power of stopping X-rays is proportional to the density of the interposed material. Thus lead foil is efficient in stopping the rays and is greatly used in X-ray practice as a protection. When these rays strike the surface of a polished mirror they are not reflected back as are ordinary light rays, but are scattered diffusively, just as ordinary light is scattered by a white surface. Regular reflection can take place only from a polished surface upon which the unevenness of surface is less than a wave-length in diameter. When we polish a metal surface we make minute scratches upon it, but the diameter of these scratches is less than a wave-length of ány of the colours in the spectrum. X-rays have a wave-length so short that no surface can be polished smooth enough for their reflection.

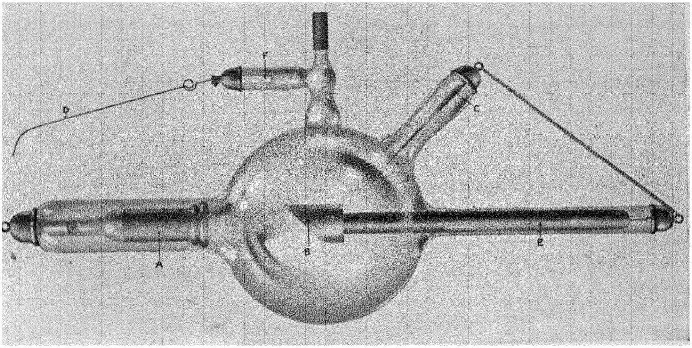
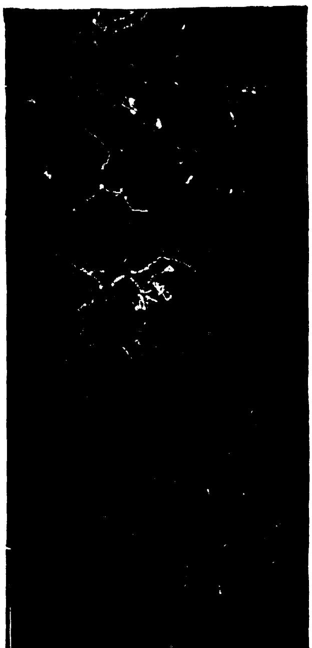


Fig. 47—X-ray tube



Cambridge Instrument Co.

Fig. 48.—Ionization by an X-ray tube

Facing page 122

The X-ray tube has undergone many improvements; fig. 47 represents a modern form.

The cathode A is made of aluminium, the surface of which (facing B) is concave, in order to concentrate the rays on to the target B. It is found that aluminium is the least disintegrated by the action (note that, at the same time as electrons are shot off from A, positive particles tend to stream the other way, and act upon the aluminium surface). The anti-cathode B consists of a heavy copper cylinder cut obliquely, in which is imbedded tungsten (not shown in figure); upon this tungsten disc the cathode stream is concentrated. Platinum is frequently used, for the amount of energy of the cathode stream which is converted into X-radiation increases with the atomic weight of the target. The connecting rod between B and the terminal is hollow, and exposes a large surface in order that the heated target may be cooled by radiation. The anode C is connected to the anti-cathode; this appears to steady the discharge.

The tube is exhausted so that the Crookes dark space occupies it entirely, excepting for a small distance about the anode. The greater the exhaustion of the tube the greater the penetrating power of the rays. With use the exhaustion of the tube increases and the rays become very penetrating. A new tube always contains a certain amount of gas which is given off from the glass and the metal of the electrodes; the shadows of the bones which it casts are very black. The rays given off in this case are said to be " soft ", in contrast to the penetrating and " hard " rays of a well-used tube. This hardness can be broken down by means of the auxiliary electrode D. When the exhaustion of the tube increases (i.e. the pressure of the residual air becomes excessively small), the resistance increases also, and a spark, owing to induced charge, travels from D to the cathode. By this spark the absor-

bent substance in the side tube F is heated slightly and liberates gas which reduces the exhaustion of the tube. So that the penetrating quality of the rays can be varied within wide limits.

The X-rays are not deflected by a magnet; they are not made up of flying particles electrically charged, but are of the same nature as light waves.

One of the most remarkable properties which they possess is the power of discharging an electroscope. It was shown that cathode rays would cause such a discharge. This we might expect owing to the charges carried by the cathode stream, but X-rays are devoid of charge (for they are not deflected by a magnet). In what way then do they bring about the discharge of an electroscope?

If air through which X-rays are passing is drawn into an electroscope with leaves charged, the leaves will collapse. If the air is first filtered through glass-wool, or bubbled through water, the leaves remain unaltered. It is therefore concluded that the air contains charged particles which make it a conductor. These particles or *ions* are produced by the X-rays.

The latter may be first passed through a piece of wood, and the electroscope placed to one side, out of the direct beam of the rays. Owing to the scattering of them by their passage through the wood, rays diverge in all directions and the electroscope is discharged.

Secondary radiation has been produced by the impact of the X-rays upon the wood, there is a scattering of the rays; moreover, there are electrons moving with high velocity. Electrons are torn from the particles of gas, and there are thus produced positively and negatively charged particles or ions.

We may construct a picture of these happenings. Let us assume that the tungsten target of an X-ray tube

is enormously magnified, to such an extent that the atoms which constitute it appear quite large, and the electrons, $\frac{1}{1800} \times \frac{1}{184}$ [1] of their mass, are just visible. We shall see flying swarms of electrons striking the target. The effect of their blows upon the mass of the atom will be great, producing vibration whose mechanical energy will be converted into heat. But the attendant electrons round the nucleus of the atom will vibrate with enormous rapidity, giving rise to waves in the ether of extremely short wave-length. These ripples of terrific rapidity will travel out from the target in straight lines through the ether with the speed of light. On reaching the glass walls of the tube they will receive a momentary check, and the electrons of the glass will be set vibrating, giving rise to a *fluorescence*.

The light waves—the X-rays—will pass out of the tube and strike the air particles whose molecular structure we shall be able to see. Here they will give their energy once more to the electrons, causing them to vibrate and give rise to more vibrations in the ether of the rapidity of X-ray vibrations. During this violent agitation we may see the electrons torn from their moorings to the atomic nucleus, and free to move on as negative charges of high velocity. The abandoned nucleus now possesses a positive charge. We see these charged ions, one the flying electron, the other the slower and enormously greater portion of the atom, attracted to their destinations by charges of opposite sign. The air is now a conductor of electricity.

The objection may be raised that this picture is purely a conjecture. That to a certain extent is true; we shall never be so fortunate as to see such an enormous magnification as that suggested above. We may never be able

[1] The atomic weight of tungsten is 184.

to see the atoms, much less the electrons. Nevertheless, the above picture is founded on fact. The existence of the electrons is beyond doubt; it has also been established by Goldstein that there is a stream of positively charged particles. By making exceedingly minute tunnels in the cathode, he showed the existence of a stream of these particles, moving in the opposite direction to the cathode stream. The ratio $\frac{e}{m}$ for these positively charged corpuscles was shown to be of the same order of magnitude as for the hydrogen ion. Further, it has been shown that electrons can be detached from the surfaces of metals by ultra-violet light just in the same way as they are detached from the air particles by X-radiation. This effect is called the *photo-electric effect.* It would be easier to explain if we could assume, as was first believed by Newton, that light consists of corpuscles projected with the velocity of 186,000 miles per second, instead of waves in the ether as the modern hypothesis states.

The ionizing power of X-rays is far greater than that of ultra-violet light; the latter is usually not sufficient to detach an electron from its atom. The electrons are so distorted from their orbits round the atoms that they are capable of attracting neutral atoms, thus forming negatively charged ions. The X-rays produce rapidly moving electron streams (i.e. cathode rays), and these streams can be made visible by the ions they produce.

Fig. 48 (see plate facing p. 122) shows a photograph of X-ray ionization. This photograph was originally made by Mr. C. T. R. Wilson and published in the Proceedings of the Royal Society. When moist air is expanded suddenly it cools and moisture is deposited in the form of a cloud. If, however, the air is absolutely free from dust particles no cloud is formed on expansion. If a narrow X-ray beam is passed through the vessel it

produces ionization and each ion acts as a nucleus round which moisture is deposited. If illuminated by a strong light the moisture particles condensed round the ions appear as bright beads. In the photo the positive and negative ions have been separated by an electric field (p. 117) before the water condensed upon them.

It was shown by C. T. R. Wilson that drops of water would condense on the negative ions when a certain expansion of the moist air was reached. If the ions are formed by ultra-violet light they will each carry the charge of one electron. Each drop has as its charge, e.

Now every drop is falling in the air owing to gravity, and it has been shown by Sir G. G. Stokes that the velocity of fall, $v, = \frac{2gr^2}{9q}$ (g = acceleration due to gravity, r = radius of drop, and q = the resistance offered by the air, its viscosity). If we measure v we can find r and hence mass M.

But suppose we attract the charged drop by an electric field (like a piece of elder pith being attracted by vulcanite), we can balance the force of attraction against the action of gravity and the drop will remain motionless in the air.

If the field strength is X, then the force of attraction on charge $e = \mathrm{X}e$. If M is the mass of the drop, force of gravity $= \mathrm{M}g$.

$$\therefore \mathrm{X}e = \mathrm{M}g. \quad \therefore e = \frac{\mathrm{M}g}{\mathrm{X}}.$$

It is assumed that all the drops are the same size. Instead of using water, Millikan used very minute drops of oil. These drops might be charged with one or more electron charges which they captured from the air ionized by X-rays. A drop could be kept stationary for hours; it

might then suddenly dart upwards to capture another charge, the whole process observed through the microscope. Millikan showed that the charge on the drop increased by a definite amount or a *multiple*. This amount was the electron charge. The calculation is the same as in the case of water.

It was found that the charge upon the negative ion, i.e. the charge of the electron e, was $1 \cdot 57 \times 10^{-20}$ absolute electromagnetic units, or $1 \cdot 57 \times 10^{-19}$ coulombs.

There are other methods which we have not space to describe by which e was computed. *All* the various methods gave results in close agreement, the mean result being that just given. Knowing the ratio $\frac{e}{m}$ the mass m can be found; it is $\frac{1}{1830}$ of a hydrogen atom; whilst the positive particle has been shown to be, in mass, of the same order as the hydrogen atom.

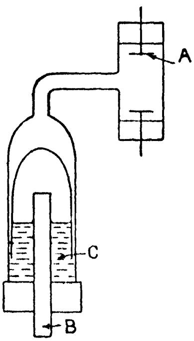


Fig. 49

How does this evidence of the existence of the electron help us in solving the mysteries of the electric current? In the first place we realize that the *negative* stream of electricity is the important one. This stream flows from the negative to the positive, and not in the conventional direction that has been assumed. For the negative stream in the cathode tube is many times more rapid than the stream of positive particles in the Goldstein rays. Moreover, there is one, and only one, negative particle or electron common to all matter, whose charge is a fixed quantity. Secondly, the number of electrons which travel either along a conductor or through an electrolyte is truly enormous; since the charge of one electron $= 1 \cdot 57 \times 10^{-19}$ coulombs, the number of electrons per

coulomb $= \dfrac{10^{19}}{1{\cdot}57}$. To produce a current of one ampere approximately 6·37 million, million, million electrons must pass in one second. The current used by an ordinary incandescent lamp is about $\frac{1}{4}$ amp. In order to count the electrons passing through this lamp per second, we will imagine that we can employ every living soul of the world's population. To modify an illustration of Professor Millikan, if everyone in the world, men, women, and children, and even the infants in arms, were to count steadily at the rate of two per second, the full tally of the electrons would not be complete in forty-four years.

In the third place, we learn that electrons are capable of being detached from their atoms, and this gives us some insight into the transmission of the current. Good conductors of electricity are those substances in which the electrons are interchangeable from atom to atom. We have always to remember that there is no such thing as rest among either atoms or electrons, so that a current is produced by the interchange of electrons. Sir Oliver Lodge describes the three ways of electric current transmission as: (1) The fire-bucket method by which electrons are handed from one atom to another along a conductor. (2) The bird-seed method; in electrolysis the ion carries its positive or negative charge like a bird carrying seed, and drops it only when the electrode is reached. (3) The bullet method, in which charged particles are shot from one point to another, as in the cathode and X-ray tubes.

The electron will explain many difficulties in electrostatics. For example, we may regard an insulator as a substance in which the electrons are more firmly bound up in the atom than they are in a conductor. For we know that the atomic structure of insulators forms a very stable arrangement. A negative charge may be

given to a conductor by friction, by separating the electrons from their positive particles. If another conductor is brought near, but separated from the first by a dielectric, no current can pass through the latter as the electrons are not free. But these electrons can be displaced, and they cause an accumulation of positively charged particles, attracted to the nearest points on the second conductor—we have induction.

At length the displacement of the electrons in the dielectric will be great enough to detach an electron, which rushes across to the positive charge; it collides with neutral atoms and converts them into ions. There is a conducting chain of ions formed, then a further rush of ions, and the collisions result in the formation of a spark. Here, then, is the reason for increased spark by illuminating terminals with ultra-violet light (see Chap. XIII).

Experiments

1. Carry out (with a small induction coil) the experiment to illustrate the fluorescence of quinine sulphate. A Wimshurst machine can be used instead of the coil.

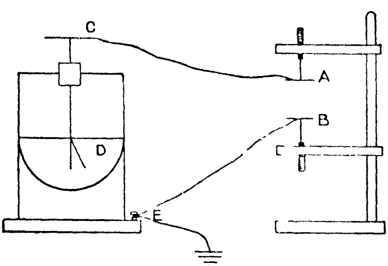


Fig. 50

2. The following experiments are suggested upon ionization. As X-rays and ultra-violet light are not easily available, the agent of ionization is radio-active material. The apparatus is illustrated in fig. 50. Two metal discs A, B with insulating handles are mounted in a wooden stand. A is connected with the cap C of the electroscope, and B with the earthing terminal. A circular protractor is placed behind the electroscope. The protractor

should read to degrees and have the five-degree divisions marked clearly. The electroscope gives the best results when it has one gold leaf only.

(1) Charge the electroscope by induction, using a vulcanite rod. See that the natural leak is very small; with proper insulation this is so. It is best to read the leaf against the scale divisions on the protractor by a reading telescope. Place the radio-active material contained in a watch-glass upon B, again charge C, and take the time for the leaf to collapse.

IONIZATION POTENTIAL.—The ions produced between A and B cause a very minute current between the plates. Now the readiness with which the positive and negative ions are conducted to A and B will depend on their potential difference. If the potential is steadily increased the current between A and B is increased—*up to a point*. When the potential is so strong that all the ions are attracted to A or B, increasing potential difference will not increase current. The potential at which all the ions are attracted is called the *ionization potential*.

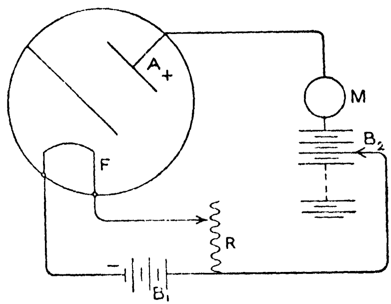


Fig. 51

(2) We can illustrate this by the apparatus. Cover the radioactive material with a thin sheet of aluminium foil; the rate of collapse of the leaf will be much slower. (If aluminium screens off too much of the rays use stout cardboard.) Take the time for the collapse of the leaf through successive amounts of five degrees. Plot these times against the number of degrees of collapse from 60° to 0°. What kind of curve do you get?

The rate of collapse is proportional to the ionizing current between A and B, and this current is proportional to the potential difference between the plates, and this again is indicated by the position of the gold leaf.

(3) Ratio of current from filament to anode of a thermionic valve to potential difference between filament and anode. A wireless valve is set up with connexions as in fig. 51. The

filament F is lighted with a *constant* current from battery B_1, controlled by resistance R. The anode A is connected through the milliammeter M to the positive of the high tension B_2, which can be connected by a wander plug with B_1.

Keep the filament glowing and vary the potential of A (i.e. the potential difference between A and F) by the alteration of the number of cells of B_2 used; take several readings, and plot a graph of readings on milliammeter against potential difference between A and F. A voltmeter can be included between B_1 and B_2, though usually the voltage engraved on the battery points of B_2 is sufficiently accurate. Up to a certain point the current increases, but after that voltage is reached it remains steady (a flattening of the curve is shown in the graph); at that point all the electrons emitted by the steadily-glowing filament are attracted to the anode A. This is analogous to the attraction of the ions in the preceding experiment.

N.B.—A valve of a fairly low plate voltage should be used; it is convenient to mount it on a plate valve holder.

CHAPTER XI

RADIO-ACTIVITY

We have seen (Chapters I to III) how the idea that matter is granular in structure has risen from mere speculation to reasoned hypothesis. The hypothesis has survived such searching tests and has shown itself to be of such wide application that it has earned the title of a theory. Although we have no *direct* evidence of the existence of atoms and molecules it is hard to see how such phenomena as the Brownian movement could be explained on any other hypothesis. More recently it has become necessary to regard electricity also as granular. The knowledge that electricity never occurs in quantities smaller than $4{\cdot}65 \times 10^{-10}$ electrostatic units forces us to look on this quantity as the "atom" of

electricity, i.e. the electron. The evidence for the existence of this " atom " of electricity has been considered in Chapters VI to X, and we could hardly desire more convincing proof than that furnished by Millikan's work (p. 127).

The recently-discovered facts of radio-activity are not only of great interest in themselves, but bring important evidence to bear on our theories of the nature of matter and the nature of electricity. The law of constant composition of chemical compounds was approached from the behaviour of matter in bulk. From the behaviour of (say) a gramme of iron, containing millions of atoms, we were able to infer how a single atom would behave. All the arguments were based on the assumption that the behaviour of the individual atom could be deduced from the behaviour of a crowd of atoms. As a gramme of matter had exactly the same properties as $\frac{1}{100}$ of a gramme except that there was more of it, we were able to say that we could find no difference in the behaviour of atoms on account of the number present. But the crowds were always very large. The smallest particle that could be perceived through a microscope was a crowd of billions of atoms. When we spoke of an " individual " atom we meant the " average individual " atom.

The assumption that an individual atom would not be different from the average atom of a crowd was not unreasonable. Phenomena in the physical world are generally simpler than those of the psychological, and the fact that a human by himself can be very different from the same human in a rioting mob is no argument that atoms are not more consistent in their behaviour.

In any case the assumption could not be tested, for we had no means of studying an atom by itself. Radio-activity gives us the means of studying the individual atom and even the inner nature of the atom. As a result

we are able to confirm many of the earlier deductions concerning the atom.

The story of radio-activity begins with the discovery of X-rays by Röntgen in 1895. Inquiries were immediately set on foot to discover whether X-rays were produced by other means than the bombarding of a metal target with cathode rays. It was while investigating "phosphorescence" that Henri Becquerel discovered radio-activity.

Some substances glow in the dark. One such substance is calcium sulphide, which is largely used in the making of luminous paint. After being exposed to light, calcium sulphide itself gives out light for several hours. If kept in the dark the substance loses its power of giving out light, but it recovers after further exposure to daylight. This property of storing light energy is known as phosphorescence. It is possessed in some degree by many substances other than calcium sulphide.

Becquerel was examining phosphorescent substances to find whether they gave out X-rays as well as rays visible to our eyes. His method was to wrap a photographic plate in black paper to exclude light. [He proved that the envelope so made was efficient by developing a plate which had been covered with the paper and left in the sun for a whole day.] He placed some of the phosphorescent substance on the black paper enclosing the plate, and left it in the sun for several hours so that the phosphorescence should be stimulated. The envelope was afterwards broken, and the plate developed and examined for any marks caused by rays that had penetrated the paper. Calcium sulphide was found to give out such rays when stimulated by sunlight. [These rays have since been shown to be not X-rays, but "ultra-violet" rays.]

A compound of uranium (the double sulphate of

potassium and uranium) was found to give out remarkably strong rays. When a coin was placed between the compound and the paper a silhouette was formed on the plate, the parts of the plate under the thinner parts of the coin being affected more strongly than those under the thicker parts, e.g. the " head ". A sharp image of a metallic stencil could also be obtained. The effects could not be due to vapours given off from the substance because they were produced equally well if a sheet of glass was placed between the black paper and the substance.

The rapidity with which the next step followed was due in part to a fortunate chance of which Becquerel quickly took advantage. In order to conduct further experiments with this compound of uranium he had placed some crystals on wrapped plates on the 26th and 27th of February, 1896, but as there was little sun on those days he put the plates with the crystals still on them in a drawer. By the 1st of March he had not been able to finish the experiments, so he developed the plates to see whether the daylight had had any effect in producing even feeble rays. Instead of there being a weak image on the plate, he found to his surprise a very strong one.

Sunlight, then, was not necessary for the production of these rays. Was daylight necessary? A photographic plate and some crystals were enclosed in a box in a dark room. The box was put in another box, and the whole placed in a drawer. Strong images were found when the plate was developed five hours later.

The light rays emitted by the compound used could barely be perceived $\frac{1}{100}$ of a second after the outside light had been cut off. It was possible that the invisible penetrating rays were due to the previous exposure of the compound to light, but if that were so, it would be necessary to assume that the penetrating rays were given

out for a much longer period after stimulation than the visible light rays. Later experiments detected no decay in activity in producing these penetrating rays, however long the substance had been kept in the dark.

Another important property of the rays was discovered; they discharged both positively and negatively charged bodies. If a silk tassel is stroked with a piece of rubber (e.g. a tobacco pouch) the silk strands will become negatively charged. As the strands repel one another the tassel will spread out in a wide cone. If a compound of uranium (or of radium) is brought near it will be seen that the displayed tassel will collapse. Similarly the leaves of an electroscope charged either positively or negatively collapse as soon as a compound of uranium (or of radium) is brought near.

Becquerel was able to announce later in the same year that all the uranium salts he had tried gave out rays which could penetrate black paper and affect the silver salts in the photographic plate. He had experimented with a large number of uranium compounds, and they all produced these rays, whether they were phosphorescent or not; whether they were crystalline, melted, or in solution; whether they were freshly prepared or specimens some years old.

It might be expected that this property of uranium of emitting "Becquerel rays" would be altered by chemical combination. The element iron is affected by a magnet, but none of the compounds of iron is magnetic (except one oxide of iron and that very slightly). The only properties of an atom that remain unaltered by being combined with other atoms are the "physical constants", e.g. atomic weight. The extraordinary fact, however, emerged that the activity of a uranium compound was always proportional to the amount of uranium present. The rays, therefore, must come from the atoms

of uranium, and chemical combination of uranium atoms with atoms of other elements does not affect the emission of rays from the uranium atom.

The spontaneous generation of penetrating rays is known as " radio-activity ".

The testing of all the other elements known in 1898 revealed only one, thorium, that was radio-active. [Thorium oxide is the main constituent of incandescent gas-mantles.] The discovery of the radio-activity of thorium was made independently by Schmidt and by Mme Curie. The rays from thorium compounds affect a photographic plate much less strongly than those from uranium, but their power of ionizing the air and so causing the discharge of an electroscope is about equal to that of uranium rays.

Mme Curie was enabled to examine a large number of uranium ores through the generosity of the Austrian Government and some French societies and companies in presenting her with several tons of pitchblende residues from different mines. She tested the activity by means of the saturation currents produced between two plates on one of which the material was spread. (Cp. Experiments, Chapter X.) If the air between the two plates is ionized and a potential difference applied to the plates, the ions will enable the charge to leak across the air space, and a current will flow in the circuit. The greater the potential difference between the plates the greater will be the number of ions carried out of the gas on to the plates, i.e. the greater will be the current across the air space. If, however, all the ions are so removed further increase in the potential difference can cause no increase in the current. This maximum or " saturation " current is therefore a measure of the number of ions formed by the rays from the active substance. The stronger the rays, the greater

the number of ions formed, and so the higher the saturation current. Arrangement of apparatus required is similar to that shown in fig. 50 (p. 130). It is unfortunately not possible to reach the saturation current for radioactive substances without a high potential difference, and a very sensitive instrument for measuring the fall in potential, but the method can be inferred from the experiments on the thermionic valve (Chapter X).

The saturation currents for some samples of pitchblende were respectively $8{\cdot}3 \times 10^{-11}$, $7{\cdot}0 \times 10^{-11}$, $6{\cdot}5 \times 10^{-11}$, and $1{\cdot}6 \times 10^{-11}$ amp. Now the saturation current for uranium metal is only $2{\cdot}3 \times 10^{-11}$ amp. The minerals contained only a small proportion of uranium, and yet some of them were more active than uranium itself!

Another of the minerals examined, namely "chalcolite", gave a saturation current of $5{\cdot}2 \times 10^{-11}$ amp., while the current to be expected from the uranium in its composition was $0{\cdot}9 \times 10^{-11}$ amp. To test whether, contrary to previous experience, the increase in activity was due to the particular chemical combination in chalcolite, Mme Curie prepared in the laboratory some artificial chalcolite. The saturation current was $0{\cdot}9 \times 10^{-11}$ amp., just the calculated value. The high activity of the natural chalcolite, then, could not be accounted for by the uranium it contained.

What was the explanation? Mme Curie suggested that these very active minerals contained a small quantity of an unknown element which was much more active than uranium.

The analysis of pitchblende was a laborious task, for pitchblende is an ore that contains compounds of nearly all the metals. However, M. and Mme Curie, following the ordinary methods of chemical analysis, separated the metals into groups. The activity of the groups was tested

by means of the saturation current and those groups found active were further analysed. At last the activity was found to be concentrated in the bismuth and the barium. Now bismuth and barium are not ordinarily active, so the active bismuth and active barium were subjected to further treatment, till there was isolated from each a substance previously unknown and very active. Mme Curie named the one polonium, after her native country, and the other radium.

It will serve our purpose if we consider only radium. What is radium? Is it different in nature from the elements already familiar? The very difficulty of separating it from barium shows that radium and barium must have similar properties. To every compound of barium there is a compound of radium similar in composition and in properties. The small differences in properties are such as occur between the compounds of calcium and those of strontium or of barium. Radium evidently belongs to the same chemical family as calcium, strontium, and barium. In the separation of radium from barium advantage is taken of differences in the solubility of their compounds in water. For instance, barium bromide is more soluble than radium bromide. Therefore, if a mixture of the two salts is dissolved in water and the solution allowed to crystallize, a slight concentration of the radium bromide will occur in the crystals. That is, the solution will lose a larger proportion of radium bromide than of barium bromide. If the crystals are dissolved in another quantity of water and re-crystallized, the new crystals will be still richer in radium bromide. After this process of "fractional crystallization" has been repeated seven or eight times the crystals consist of almost pure radium bromide.

Radium then is a metal, similar to barium and not unlike calcium, and it has the properties of a normal

element. It has all the ordinary properties with the additional properties associated with its radio-activity. These are that it gives out penetrating rays under all conditions and that it is always 2° C. warmer than its surroundings. It gives out energy at a tremendous rate. A piece of radium will cause more than its own weight of water to boil in an hour. This fact is not so impressive as the fact that the same piece of radium would go on boiling water for thousands of years. Coal when burning is giving out energy, but it burns for a very short time and afterwards ceases to give energy. The most careful measurements have failed to detect any falling off in the output of energy by radium, but it has been calculated that it must decrease by 4 per cent each hundred years. That so much energy could come from so small an amount of matter was entirely outside our previous experience.

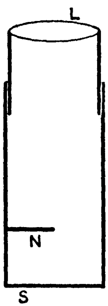


Fig. 52

Radium not only evolves energy; it shoots out tiny particles of matter known as α-particles. The emission of α-particles may be observed by means of the spinthariscope, an instrument designed by the late Sir William Crookes.

A needle N (fig. 52), the point of which has been allowed to touch a small vessel which once contained a radium salt and has therefore collected a minute trace of active matter, is mounted between a zinc sulphide screen S and a lens L. On looking through the lens the screen is seen to be fluorescent owing to the bombardment by the rays. If the lens is focused accurately it can be seen that the fluorescence is not uniform but consists of a number of flashes. Each flash is due to the bombardment of a single α-particle.

An α-particle is far too small to be seen, but, because

it lights up the zinc sulphide screen for a considerable distance round the actual point of impact, we can see the signal of its arrival on the screen.

The minute trace of radium is shooting out these α-particles at the rate of hundreds a minute, not only towards the screen but in all directions. Of those that hit the screen it is likely that only a small proportion cause a scintillation. The production of a flash of light is dependent on the crystalline state of the zinc sulphide at the point of impact. Although the screen may get worn out in about a year and require renewal, the radium will go on emitting particles with the same force and with little decrease in number for hundreds of years.

As an invisible trace of radium is the source of all these millions of particles, it follows that the α-particle itself must be very small. In fact we have ample evidence that it is a single atom of matter. The atom, which before we knew only as a unit in a crowd, is here seen acting as an individual.

The nature of radio-activity has been made clear largely by study of the rays given off. It was on account of the rays that Becquerel discovered the activity of uranium. All that was known of them at first was that they could pass through paper and that they could affect a photographic plate. There was no evidence that there was more than one type of ray. However, when thorium was found to be radio-active it was discovered that its rays had about an equal power in discharging an electroscope as the rays from uranium, but that they had a much weaker effect on a photographic plate. There was a strong probability, therefore, that there were at least two types of ray. It has since become clear that there are three types, any or all of which may be present in the radiation from a particular material. They are known as the α-, the β-, and the γ-rays.

These three types are distinguished by difference in penetrating power and by difference in the effect of a magnet on them. The rays vary greatly in ability to penetrate matter. The β-rays from radium are more penetrating than those from uranium, but β-rays as a class are 100 times as penetrating as α-rays as a class. Similarly γ-rays are 100 times as penetrating as β-rays.

The α-rays then are the " softest ". They are stopped by a thin sheet of paper or by three inches of air. Indeed any α-rays that are generated in the middle of a sample of active substance are stopped by the surrounding material before they can emerge. If, however, a small quantity of active material is spread over a large surface, as for instance by allowing a solution to evaporate, the α-rays are given off in great quantity, and their presence can be shown by the brilliant lighting of a fluorescent screen. Unfortunately it is not practicable to spread the substance in an ordinary laboratory owing to the cost of active material and the danger of wasting some of it.

β-rays can get through paper with ease, and also through cardboard, mica, and thin sheets of aluminium, but they are stopped by aluminium foil 4 mm. in thickness.

γ-rays are the most penetrating type of radiation known. The γ-rays of radium have been detected after passing through more than 20 cm. of lead.

All three types of ray have one property in common, a property which is shared also by X-rays. They can penetrate all kinds of matter whether transparent or opaque to ordinary light. It is not the nature but the quantity of matter which stops the rays. If the material is dense, like lead, it impédes the passage of the rays; if, like cardboard, it is not dense, it will offer little opposition. Ordinary light is completely stopped by many substances which allow these other rays to pass,

but as Professor Soddy has pointed out, there is no form of radiation the equal of light in penetrating those media that it can get through. The γ-rays of radium are stopped by 25 cm. of mercury. They would be stopped equally well by a column of air which balanced a column of mercury 25 cm. in height, for the amount of matter in the two columns would be the same. Such an air column would be about 3 miles high. The sun's rays, however,

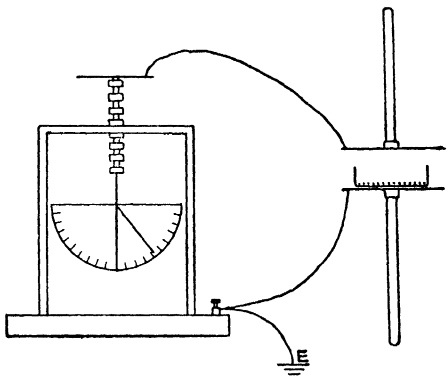


Fig. 53

reach us with very little loss after passing through three times as much air as would stop these γ-rays completely. This column of air extends for a vertical distance of about 50 miles from the surface of the earth, the upper part of the atmosphere being much less dense than that near sea-level.

The difference in penetrating power of the rays can be seen by the use of an electroscope fitted with a protractor such as has been described on p. 130. Two plates are fixed in parallel planes about 3 cm. apart, and one of them connected to the gold-leaf system (fig. 53). The other plate and the case of the electroscope are both

connected to earth. The gold leaf and the plate connected to it are then charged by means of an ebonite rod that has been rubbed on flannel. The deflection of the leaf is noted and the rate of leak (if any) is found by measuring the time taken by the leaf to fall through successive angles of 10 degrees, e.g. 70° to 60°, 60° to 50°, &c.

If a dish (e.g. a crystallizing dish) containing a small quantity of a radium salt is placed between the plates it will probably be found that the leaf collapses after charging at a rate too great to be measured. All the γ-rays, nearly all the β-rays, and some of the α-rays are ionizing the air between the plates and enabling the charge to leak away. If the α-rays are completely cut off by means of a thin sheet of cardboard the rate of leak is less, and the time taken for the leaf to fall through successive 10 degrees can be found. Similarly a sheet of lead foil can be used to cut off the β-rays, leaving only the γ-rays to ionize the air. The leaf then falls much more slowly.

The separation of the mixed rays by means of a magnet will perhaps be more clearly understood if we consider first a rough analogy.

If two ores cannot be separated by washing, they may, if one be magnetic, be separated by an apparatus shown diagrammatically in fig. 54. The mixed ore falls in a stream from a moving belt and, as it falls, crosses the field of an electromagnet. The non-magnetic ore is unaffected and falls on the heap A, but the magnetic ore is drawn towards the magnet and forms a separate heap B.

The mixed rays from an active body may be sorted out by a similar method. If the rays are passed between the poles of an electromagnet, the β-rays are strongly deflected. They behave exactly like cathode rays (p. 117).

Therefore, like cathode rays, they must be negatively charged. They are, in fact, streams of electrons moving at great speeds, which may be almost as great as the speed of light (186,000 miles per second).

The α-rays are much more difficult to deflect with a magnet, but in a powerful field they are found to be deflected in the direction opposite to that of the β-rays. They are, therefore, positively charged. In describing the spinthariscope (p. 140) it was said that the flashes

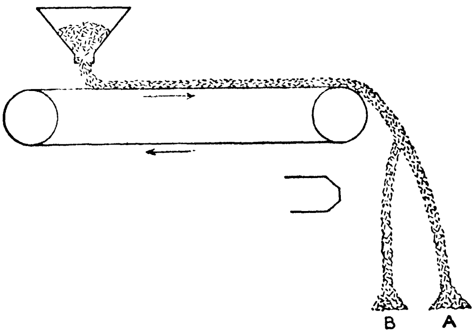


Fig. 54

were due to particles of matter. What was the nature of the evidence that the α-rays were composed of α-particles? It was obtained by Rutherford and Geiger by the use of very much " thinned down " α-rays. The apparatus was in essence the same as that used in the experiment described on p. 143. Instead of the gold-leaf electroscope an electrometer was used that was so sensitive that a tiny alteration in the charge caused a mirror to turn and so move a spot of light along a scale. The radium was placed some way off and the β-rays prevented by a magnet from reaching the electrometer plates. It was then found that the spot of light moved in jerks. These jerks could not be explained on a wave hypothesis, for

the essential feature of wave motion is that it is regular or periodic. The α-rays must then be made of separate particles in much the same way as a stream of falling lead shot is composed of separate spheres of lead.

The amount of the deflection in a magnetic field tells us the ratio of charge to mass, just as it told us the ratio $\frac{e}{m}$ for the electron in the cathode rays. It was found that if the charge e was the same in amount as, though differing in sign from, the charge carried by an electron, then the mass of the α-particle was about 2. α-particles have since been identified with helium atoms, which have a mass 4. Hence it follows that the charge carried by an α-particle is twice the charge on an electron, for $\frac{2e}{4} = \frac{e}{2}$.

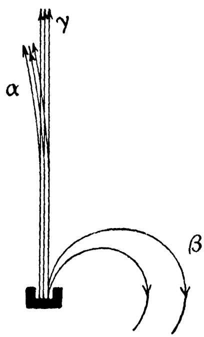


Fig. 55

The γ-rays are not affected by a magnet. They have been examined by the X-ray spectroscope (p. 179) and found to be of the same nature as X-rays. That is, they are not composed of material particles. They owe their great penetrating power to their very short wave-length and very high frequency (see p. 170).

The behaviour of the three types of ray is illustrated by the diagram in fig. 55 (after Mme Curie).

Experiments

1. Examine a specimen of calcium metal (which is similar to radium metal).

2. Heat some calcium in a crucible and so obtain calcium oxide (quick-lime). Add water drop by drop to a little cold

calcium oxide. Calcium hydroxide (slaked lime) will be formed. Dissolve it in water, filter, and divide the clear solution into two parts. To one part add dilute sulphuric acid and so obtain calcium sulphate (gypsum). Into the other pass carbon dioxide (e.g. from the lungs) and notice the formation of calcium carbonate (chalk).

Radium forms similar compounds.

3. Perform the discharging experiment described on p. 136, either with a silk tassel or with a " head " of hair.

4. Perform the ionization experiment described on p. 143.

5. Examine the scintillations in a spinthariscope.

6. Connect a single cell through a 50,000-ohm resistance to a moving-coil galvanometer. Note how the slight movements of the coil are magnified on the scale.

7. Try to separate lead iodide and potassium nitrate by " fractional crystallization ". If solutions of lead nitrate and potassium iodide are mixed, lead iodide (yellow) and potassium nitrate will be formed. Lead iodide is much less soluble than potassium nitrate, but it is fairly soluble in hot water.

CHAPTER XII

RADIO-ACTIVITY (*cont.*)

THE TRANSFORMATION OF THE ELEMENTS

As far back as 1899 it was found that thorium produced a radiation which could be blown about by air-currents. It was almost certainly matter, for rays cannot be blown about. It could not be α- or β-particles for they are expelled at such a speed that they are not deflected by a draught. This " emanation ", as it is called, must therefore be either a cloud of dust or a gas.

Dust particles act as nuclei round which water drops collect when wet air is chilled, but this emanation did not provide nuclei for the formation of mist. Moreover, it could pass through cardboard, so it was probably not dust.

It might be air that had been ionized by the rays from the thorium, but ions give up their charge when passed through cardboard or when bubbled through solutions. The emanation retained its activity after being tested in these ways.

Similar emanations are given off by radium and actinium but not by uranium. By exhaustive tests they were shown to be gases. They diffused through a porous plate, they could be compressed, and they could be liquefied. They were unchanged by strong heating, and survived treatment by even the most violent chemical methods. They could not be made to combine with any other substance. They were therefore included in the argon family of "inert" gases.

How do these emanations come to be associated with radio-active solids? Ordinarily they are stored in the interstices of the solid, but if the solid, radium bromide, for instance, is dissolved in water, the whole of the imprisoned emanation is set free. The emanation may be stored in a flask, and the radium bromide may be recovered from the solution by evaporating off the water.

The emanation is found to be strongly radio-active, and the radium bromide recovered from solution is found to have a very low activity compared with what it had before the emanation was removed. It is the trapped emanation therefore that is responsible for most of the activity of radium bromide.

When recovered from solution, then, radium bromide has a relatively low activity. Its activity, however, gradually returns and after a month is not perceptibly less than it was before the emanation was removed. If it is again dissolved in water another crop of emanation can be obtained, and this process may be repeated any number of times. Fresh crops of emanation may be taken from

the one sample of radium salt without any apparent exhaustion of the source of supply.

Meanwhile, what has happened to the emanation that was stored in the flask? Its activity has waned as that of the radium bromide has increased. At the end of a month no active emanation can be found. There is only an active deposit on the walls of the flask.

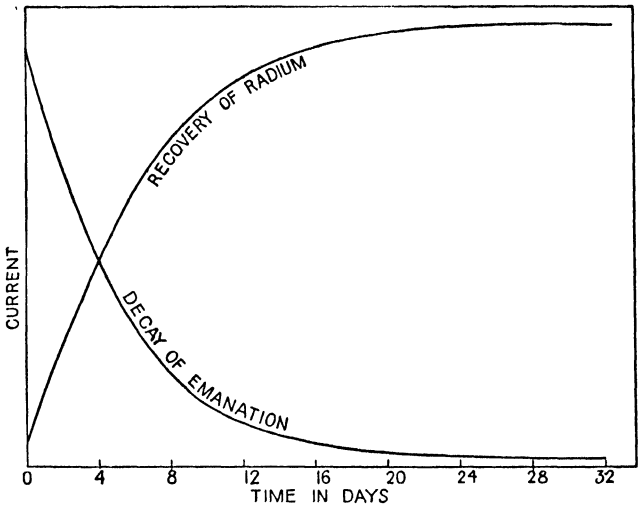
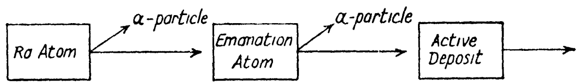


Fig. 56

Fresh crops of emanation may be obtained but it cannot be stored without losing its activity. If the activity of radium bromide from which the emanation has been removed be measured from day to day, and that of the emanation be also measured from day to day, it is found that the sum of the two activities is always the same. The recovery of the radium is exactly balanced by the decay of the emanation. The form of the two curves is shown in fig. 56. The activity is measured by the saturation current.

The only satisfactory explanation of these extraordinary phenomena is that of Rutherford and Soddy. They had obtained from thorium a highly active substance (thorium X), which gradually lost its activity while the thorium from which it had been separated regained its lost activity. Their suggestion was that the radio-active elements changed into other elements. This was revolutionary. Were not atoms the unchangeable bricks of which matter was built? What of Newton's particles " so hard as never to wear away or break in pieces "?

On their hypothesis a radium atom broke up into an α-particle and an atom of emanation, which also broke up into an α-particle and an atom of " active deposit ". Expressed graphically their view was:



There was another line of approach to the knowledge that one element could produce others. When Sir William Ramsay discovered helium on the earth in 1895 the source of the helium was clèveite, which is an ore containing uranium. It was later found in other minerals, all of which were later found to be radio-active. Then it was shown that all radio-active minerals contained helium stored up in the pores of the solid. The amount of helium is sometimes small, but some minerals have yielded nearly a hundred times their own volume of helium.

Before the discovery of radio-activity it was impossible to account for the presence of helium in ores of uranium and thorium, but in their disintegration hypothesis Rutherford and Soddy suggested that helium was one of the products of radio-active change. The fact that it accumulated in minerals would be explained if it were

one of the final products, that is, substances produced by radio-active change, but not themselves breaking up. True, emanation collects in the minerals, but there never exists more than a very small amount because it decays as fast as it is produced. The quantity is so small that it would not have been discovered if it were not giving out a huge amount of energy as it decayed. It was suggested that helium had been formed in these minerals through geological ages and stored there until released by Ramsay.

Ramsay and Soddy tested this hypothesis in 1903 by "growing" some helium from radium emanation, which was chosen for the experiment because of its rapid decay. Some emanation was sealed up in a small spectrum tube, so that the spectrum of the gas could be examined at intervals. After three or four days the helium lines appeared in the spectrum and got stronger and stronger until they were fully developed. Helium, then, is a product of the decay of radium emanation.

The helium atom is four times as heavy as a hydrogen atom. On p. 146 it was stated that the deflection of α-particles by a magnet told us that the ratio of charge to mass was such that if the charge was single then the mass was 2. If the α-particle has mass it was almost certainly matter, and probably either hydrogen or helium. Even without proof that the α-particle carried a double charge and was therefore of mass 4, it was possible that this was so, and that the α-particle was an atom of helium.

Rutherford has tested this hypothesis in the following manner. The apparatus is shown diagrammatically in fig. 57. A glass tube A with very thin walls was sealed into a wider vessel B, which was connected to a spectrum tube C. The glass walls of A were thin enough to allow α-particles to get through, so that when emanation was put into the tube A some α-particles would get into tube

B. Rutherford found that when emanation was in A, the spectrum of helium gradually developed in C. The gradual appearance of the helium in C could not be due to a leak, for none appeared when helium was confined in A, even under pressure.

The α-particle then is an atom of helium carrying a double positive charge, or as we prefer to say now, it is an atom of helium that has lost two electrons.

A further test is possible. If an α-particle has a mass 4, as deduced above, then an atom of radium emanation should have a mass 4 units less than that of a radium atom. The atomic weight of emanation would be difficult to find, but we can find the atomic weight of "uranium lead", which is the last element in the chain and apparently inactive. Five α-particles are lost before an atom of radium becomes an atom of lead, so we should expect the atomic weight of uranium lead to be 20 units less than that of radium (226) i.e. 206. By experiment it is found to be 206·05, which agrees sufficiently closely with the calculated value to establish the identity of the α-particle with the helium atom.

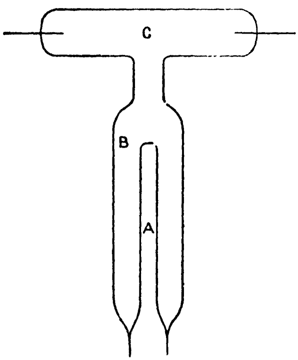


Fig. 57

At last the dream of the alchemists has come true. It is to be noted, however, that his modern transmutation of elements is entirely outside our control. It cannot be started, stopped, or altered by any known method. The rate of decay of a radio-active element is the same in whatever chemical compound it is contained. It is the same at red heat as at the temperature of liquid air.

We have not been able to affect the rate of decay in any degree.

Careful examination has shown there are long chains of radio-active elements. We infer that an atom of uranium becomes an atom of " uranium X_1 ", which breaks into an atom of " uranium X_2", and so on. Of the many points of interest in connexion with these chains we will notice here only two. First, each atom while it exists behaves like an atom of an ordinary inactive element. It has all the properties of a normal element, with the one additional characteristic, that it may at any moment change into the next element down the scale. It is a perfectly well-behaved Dr. Jekyll until it suddenly becomes a Mr. Hyde.

The second point is that any individual atom may last for any length of time. It may become " active deposit " the moment after it has become emanation, or it may remain an atom of emanation for an indefinite time, long after all the emanation atoms produced from radium about the same time have broken up. Atoms of each element, however, have an " expectation of life ". The average life of a uranium atom is 8,000,000,000 years; that of a radium atom is 2,400 years; that of an atom of radium emanation 5·6 days. Some substances have an average life period of less than one thousandth of a second. So far as we can see there is no order of stability in the chain of radio-active elements; stable and unstable elements follow one another without any apparent method.

The expectation of life of a radio-active atom is computed from statistical evidence. It is found that the rate of decay is proportional to the amount of substance present; that is, a fixed proportion of the number of atoms present must break up each second. From the time taken for the substance to decay to half its original quantity the period of average life may be calculated.

The period of average life is always 1·443 times the half-value period. For instance, the half-value period of radium emanation is 3·85 days, so the period of average life is $3·85 \times 1·443 = 5·6$ days. From the rate of production of radium emanation the rate of decay of radium can be calculated. The half-value period is about 1600 years. Therefore, if 2 mgm. of radium had been sealed up in a tube in the year A.D. 300, we should now find 1 mgm. of radium. There would also be 0·09 mgm. of helium, and 0·9 mgm. of lead, together with a small quantity of the intermediate elements.

It has already been mentioned (p. 153) that atoms of an active element behave like ordinary atoms right up to the moment of their disintegration. They combine with other elements to form chemical compounds, which have ordinary chemical properties with the extra properties due to the breaking up of a certain proportion of the atoms. If this is so we might expect the active elements to find places in the periodic classification of the elements. They all readily group themselves with the known elements. Thus uranium is similar to tungsten, and is placed in the same group. Similarly, radium is grouped with barium, and radium emanation (niton) with the argon gases. The full table including the active elements is given at the end of the book. The elements known to be radio-active are those between lead and uranium.

In 1911 Soddy pointed out that if an element lost an α-particle it was transformed into the element two places down the periodic table, i.e. two places to the left. Thus radium (group 2) became radium emanation (group 0). Fleck found this rule to hold for all the radio-active substances that he could investigate. From Fleck's work it was also discovered that the loss of a β-particle caused a shift one place to the right, e.g. from group 4 to group 5.

An obvious question arises. If we move two places to the left and then two places to the right, are we back at the place from which we started? If an α-particle and two β-particles are expelled, what is the chemical nature of the final element? The answer is that its chemical nature is identical with that of the original element; the chemist can find no difference at all between the two.

Suppose we have the chain—

$$\boxed{A} \xrightarrow{\alpha} \boxed{B} \xrightarrow{\beta} \boxed{C} \xrightarrow{\beta} \boxed{D}$$

we can write it thus—

$$\begin{tikzcd}
& \boxed{C} \arrow[r, "\beta"] & \boxed{D} \\
\boxed{B} \arrow[ur, "\beta"] & & \boxed{A} \arrow[ll, "\alpha"]
\end{tikzcd}$$

If A is in group 6 of the periodic system, B is in group 4, C in group 5, and D in group 6 again. A and D are not only in the same group or family as, for example, are chlorine and bromine, but they are in the same *place* in the table. They are, therefore, called " isotopes ".

Is there no distinction between isotopes? Is D identical with A in all respects or only in chemical behaviour? Clearly A and D must differ in mass. As the α-particle has a mass of 4 units, the atomic weight of B must be 4 units less than that of A. The β-particle, being an electron, has a mass of $\frac{1}{1800}$ of a unit, so that C and D will not differ much in atomic weight from B. Therefore, D has an atomic weight approximately 4 units less than A.

They must differ also in radio-active properties, for D is farther on in the disintegration series. It might even be the last element in the chain, the end-product of the series. It might give out an α-particle and become

E, an isotope of B, or it might split off a β-particle and move a place farther to the right.

Uranium I and uranium II are isotopes, corresponding with A and D respectively. Chemically they are identical, simply " uranium ". Chemical tests cannot detect any difference between them, yet if the atomic weight of uranium I is 238, that of uranium II must be 234. Both are radio-active and emit an α-particle when they break up, but uranium I lasts on the average 200 times as long as uranium II before breaking up.

The conception of isotopes was of tremendous interest to chemists. We had followed Dalton in supposing that the atoms of an element were all exactly alike. Since chemical analysis would be unable to detect the difference between isotopes, it might turn out that what had been supposed to be a pure element compound of exactly similar atoms was really a mixture of isotopes. If so, the carefully determined atomic weights would be no more than the average of the atomic weights of isotopes present in unknown proportions.

A " test case " was taken. Lead is, so far as we know, the end product of all the chains of radio-active substances. A study of these different chains leads us to expect that the lead from the uranium series should have an atomic weight of 206, and that the lead from the thorium series should have an atomic weight of 208. Lead ordinarily has an atomic weight of 207·2. It was shown without doubt that if lead contained a high proportion of lead from uranium its atomic weight was less than 207, and that the presence of much " thorio-lead " caused the atomic weight to be well above 207. Atoms then could have the same chemical properties even though their masses were different. The atomic weight ceased to be the fundamental constant to which chemical properties could be referred.

There could be no doubt concerning the existence of isotopes among the radio-active elements. Were any of our ordinary elements mixtures of isotopes? Attempts were soon made to find out. Chlorine was one of the earliest to be attacked. If it consisted of isotopes then the mass of some molecules would be less than the mass of others, and the lighter ones should be able to diffuse more rapidly through a porous plate. Experiments were made, but the separation, if any, was too small to permit a definite conclusion being drawn.

Since 1919, however, Dr. F. W. Aston has been using a method of "mass spectrum analysis" based on Sir J. J. Thomson's work on positive rays, and has shown beyond doubt that many of the ordinary elements consist of mixtures of isotopes. The method cannot be described here, but some of the results will be given.

Chlorine has an "atomic weight" of 35·5, but there are no atoms of chlorine of this weight. Some atoms of chlorine have an atomic weight 35 and some 37. More have the weight 35 than 37, so the average atomic weight (35·5) is nearer to 35 than to 37. Since the proof that two isotopes exist there have been more determined attempts to effect a partial separation. The diffusion process has been continued longer, and a difference (amounting to 0·155 per cent) in the density of the two "fractions" has been observed.

Argon is interesting in view of the "anomaly" of its atomic weight in the periodic classification (see p. 51). It is found to consist mainly of atoms of mass 40, with a small proportion of mass 36. Most potassium atoms have a mass 39, though some are of mass 41. Some of the potassium atoms, therefore, are heavier than some of the argon atoms. We have—

36	39	40	41
Argon	**Potassium**	**Argon**	**Potassium**

Argon being rich in atoms of mass 40 has an average atomic weight 39·9, while potassium being composed mainly of atoms of mass 39 has an average atomic weight 39·1. The anomaly of argon and potassium is made less mysterious.

It is of interest to consider the three elements bromine, krypton, and rubidium which follow one another in the order of atomic weights, which are 79·92, 82·92, and 85·45 respectively. Aston finds that both bromine and rubidium consist of two isotopes, and krypton of six. The three elements form a complete series, with atoms of mass ranging from 78 to 87, thus:

Kr	Br	Kr	Br	Kr	Kr	Kr	Rb	Kr	Rb
78	79	80	81	82	83	84	85	86	87

The atomic weight 82·92 of krypton is, of course, the average atomic weight of its component isotopes, and it is evident from such a series that we are fortunate in having only three anomalies in the periodic system.

Aston's method is capable of detecting a difference of 0·001 units in atomic masses. The very interesting result appears that, within these limits of accuracy (0·001 either way), the masses of all atoms are whole numbers except hydrogen atoms, which have a mass 1·008. [If hydrogen is taken as 1, then all the other atoms are not whole numbers, oxygen for instance being 15·88; but if we take oxygen as 16 then all except hydrogen are whole numbers.]

In 1805 it was noticed by Prout that many atomic weights were nearly whole numbers, and he put forward the hypothesis that they were all really whole numbers though some might have been wrongly determined by experiment. He extended his hypothesis by saying that all the elements were composed of hydrogen. The old idea of a prime matter or "protyle" was thus revived.

Prout's hypothesis was attractively simple, and many

atomic weights were measured again to see whether the new values would be whole numbers. Since, however, many atomic weights refused to come into line the hypothesis was discarded. As a working hypothesis it was useless as it did not fulfil the first condition, that of agreeing with known facts.

Nevertheless the number of elements with atomic weights nearly whole numbers was greater than could be accounted for by chance, so there has always been the feeling that there must be some truth behind the hypothesis. Aston's work, more than 100 years later, has shown the reason for the divergencies from the "whole-number rule". Elements like carbon and nitrogen that are simple have whole-number atomic weights, but elements like chlorine which are composed of isotopes have fractional atomic weights. (See Appendix.)

All through the ages philosophers have been attracted to the idea of a single origin of all matter. The doctrine of evolution dominates the thought of our time, and chemists have hoped that a scheme could be found to account for the existence of our different elements. The discovery of radio-active change gave a new impetus to the inquiry. Here are elements being produced from heavier elements. Perhaps even the common elements have been evolved from heavier elements? If so all elements must at one time have been radio-active; why are they apparently inactive now? There are two possible answers.

The present condition may represent a "frozen" chain of disintegration. True, we know of no means of checking radio-active change, but it is not impossible that a change in conditions has killed the activity of the elements now inactive. Alternatively, it may be that all elements are even now active although most of the changes are too slow and too gentle to be detected by us. Radio-

activity was discovered on account of the enormous amount of energy set free when one element changes to another. An α-particle, for instance, is far too small to be seen by the aid of the most powerful microscope, yet it is shot out from an atom of radium with such a velocity that it lights up a zinc sulphide screen. We have no means of detecting α-particles sent out with small velocities, so elements apparently dead may really be feebly active.

One thing is certain: if an atom of radium splits into an atom of helium and an atom of emanation, then the atom of radium must have a structure. It cannot be "radium all through". Whatever it is that makes up emanation and helium must also make up radium.

Can radio-activity tell us anything of the inner nature of atoms? Since β-particles are emitted by many elements we must suppose that electrons exist within the atom. α-particles, consisting of atoms of helium bearing two positive charges, are also sent out, so it is likely that we have helium atoms, and both positive and negative charges. Atoms are normally electrically neutral, so there must be an equal number of positive and negative charges.

The atom of helium seems to be one of the bricks of which other atoms are built. If it were the only brick we might expect all other atomic weights to be multiples of 4. Many elements have atomic weights that can be expressed by the formula $4n$, where n is a whole number, for instance, carbon (12), oxygen (16), and calcium (40); but there are others the atomic weights of which have the formula, $4n + 3$, $4n + 2$, or $4n + 1$.

Mention must now be made of Rutherford's experiments on the artificial disintegration of nitrogen atoms by means of swift α-particles. An α-particle has a mass nearly four times that of a hydrogen atom, so it was to be expected that, if an α-particle hit a hydrogen atom,

then the hydrogen atom would be thrown forward with a greater velocity than that of the original α-particle, just as a railway goods wagon is sent off at a greater speed than that of the engine that is shunting it. It was found to be a fact that, when α-particles passed through hydrogen gas, numerous faint scintillations could be observed on a zinc sulphide screen placed far beyond the range of the α-particles.

An atom of nitrogen is about 14 times as massive as an atom of hydrogen, i.e. $3\frac{1}{2}$ times as massive as an α-particle. If it were hit, therefore, by an α-particle its range would probably be less than that of an α-particle that got through the gas without collision. It was found however, that scintillations were produced at distances beyond the range of the α-particles, indeed, at a distance little short of the range of hydrogen atoms. How could the heavy nitrogen atoms have been projected with such speeds? Rutherford in discussing his results said: "From the results so far obtained it is difficult to avoid the conclusion that the long-range atoms arising from the collision of α-particles with nitrogen are not nitrogen atoms but probably atoms of hydrogen or atoms of mass 2. If this be the case we must conclude that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift α-particle, and that the hydrogen atom liberated formed a constituent part of the nitrogen nucleus."[1]

The difficulty of testing the hypothesis lay in the extremely small quantity of matter involved. Rutherford himself has said that even if hydrogen were produced one would need to work with the α-particles from a gramme of radium—more than is at present known to exist—for 1000 years to produce enough hydrogen to be detected even by the spectroscope.

[1] *Philosophical Magazine*, XXXVII (1919), p. 586.

The particles have, however, been deflected by a magnet. The long-range particles resulting from the passage of α-particles through hydrogen are also deflected by a magnet, and they cannot be anything but hydrogen. Under comparable conditions the deflections are found to be indistinguishable, so we may take it as proved that hydrogen particles are produced when α-rays pass through nitrogen.

Five other elements give the same result. They are boron, fluorine, sodium, aluminium, and phosphorus. The atomic weights of these elements are 7, 19, 23, 27, and 31 respectively. That of nitrogen is 14. Each of these atoms' weights may be expressed by one of the formulæ $4n + 3$ and $4n + 2$. It is possible that the atom of aluminium, for instance, is composed of 5 helium atoms and 3 hydrogen atoms, and that it is one or more of these hydrogen atoms that is broken off by the impact of the α-particle.

In all probability, therefore, atoms contain helium atoms and some also hydrogen atoms. We have not brought forward any evidence on the nature of helium or hydrogen atoms, so we cannot say whether helium and hydrogen atoms are ready-formed inside more complex atoms or whether they are formed out of the wreckage of the complex atoms. For example, are there inside the radium atom an atom of helium and an atom of emanation, or are all three atoms made up of the same " materials ", so that when the radium atom breaks up the " materials " re-group into a helium atom and an emanation atom? If all atoms are composed of the same " materials ", what are these fundamental " somethings " and how do they by different groupings make up our atoms?

Rutherford's suggestion was that all atoms consisted of a central nucleus carrying a positive charge of elec-

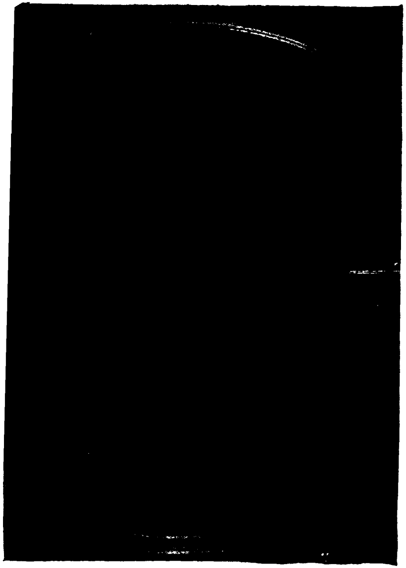


Fig. 58

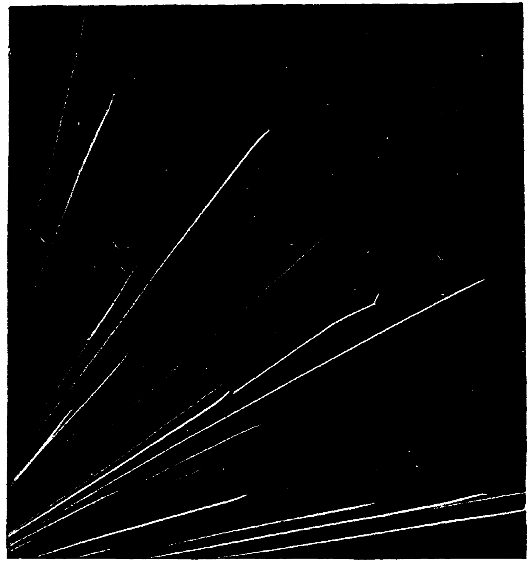
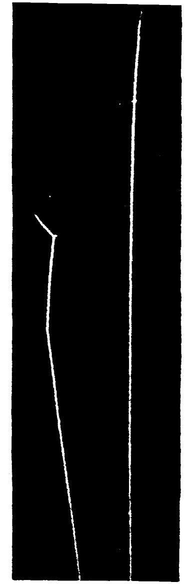


Fig. 59



Cambridge Instrument Co.

Fig. 60

α-RAY IONIZATION TRACKS

Facing page 162

tricity and satellite electrons revolving round the nucleus like planets round the sun. Evidence for this view is obtained from the behaviour of α-particles when stopped by matter. When an α-particle passes through air the air is ionized along the track of the particle. These ions will act as nuclei round which drops of water can collect just as dust particles do in the formation of fogs. C. T. R. Wilson has made visible the tracks of the rays by the following method. The air inside a box was freed from dust by allowing the particles to settle on to a layer of grease, and then saturated with moisture. When a sudden cooling of the air produced no mist it was supposed that there were no dust particles left upon which the water drops could condense. α-particles were then allowed to shoot into the air in the box, and the temperature suddenly lowered so that a drop of water condensed round each ion formed by the passage of the α-particle. The line of water-drops formed a streak of mist which was brightly illuminated and photographed. The track of an α-particle could therefore be studied over its whole length from its entrance into the air until its velocity became too small for it to ionize any more air. Photographs of the tracks of some α-rays are reproduced in figs. 58–60.

It will be seen that the paths are mainly straight, that they are occasionally bent slightly from the original direction, and that some of them show an abrupt change of direction just before the end. There may also be observed a slight spur where an α-particle has been sharply turned to one side. It is reasonable to suppose that these large deflections are due to collision with an atom, and that the spur is due to ions formed by the atom when recoiling from the shock of the collision. If this is so then many α-particles travel through several centimetres of air before they hit an atom. Yet on their

journey they must have passed by a very large number of atoms and actually passed *through* many thousands of atoms. Indeed, they have ionized the air; that is, they have torn off electrons from the atoms they have passed. Each ion so formed has collected a drop of water round it and so become big enough to be seen. The drops are so close together that we cannot see any space between them. Why, then, does the α-particle get as far as it does before being stopped?

Suppose an observer on the edge of our universe had measured the diameter and the mass of the solar system, so that he knew the size of it and the amount of matter in it. Suppose also that he fired a large number of " worlds " at it. If he found that most of his projectiles went through the solar system and that a small proportion collided violently as if with massive bodies, he would be justified in deducing that the matter in the solar system was concentrated in lumps and that the remainder was empty space.

Similarly an atom cannot occupy all the space it seems to. We know the diameter of an atom, yet a great part of this diameter must be empty space. Exact measurements of the deflections bring us to the conclusion that almost the whole of the matter is concentrated in an exceedingly small central nucleus. At relatively enormous distances from this massive nucleus rotate electrons in different orbits. Ordinarily the effective size of an atom is the size of the orbit of the outermost electrons. It is only by special means, e.g. the firing of swift α-particles at the atom, that we are able to penetrate these orbits and occasionally reach the nucleus.

The structure of the atom is further considered in Chapters XIV and XV.

CHAPTER XIII

THE SPECTRUM

The fact that light travels in straight lines and the laws governing its reflection have been known since very early times. In 1621 Snell discovered that when light passed from one transparent substance to another, e.g. from air to glass, it was bent according to a definite law. The sine of the angle which the beam of light made with the perpendicular in the air, divided by the sine of the angle made by the bent beam of light with the perpendicular in the glass, was a constant quantity.

In 1666 Sir Isaac Newton passed a narrow beam of white light through a prism; he found that a band of the colours of the rainbow was formed, which could be thrown upon a screen. This band of colours is called the spectrum. Newton came to the conclusion that white light contained the seven colours, red, orange, yellow, green, blue, indigo, violet, as a mixture. It was the function of the prism to separate them out. He believed also that light consisted of beams of minute particles—it was corpuscular.

This view was opposed by Huygens, who suggested the theory that light consists of waves—*mechanical* waves in some medium. Since light travels from the sun to the earth through empty space Huygens made the mysterious ether the carrier of these waves. Though Newton and Huygens disagreed as to the nature of light they both affirmed one important point, that light, whatever else it is, is a periodic happening, both in time and space.

To realize the meaning of this let us take the case of the simple pendulum swinging about its central point. A point A, at the centre of the bob, will during one swing accomplish a definite journey. It will pass from

its highest position on the left, through the lowest point of its swing, then to its highest position on the right, then back again through the same points. Let us say that the time it takes for the complete journey and *back* is 1 sec. After $\frac{1}{4}$ sec. from the start it is passing through the lowest point, after $1\frac{1}{4}$, $2\frac{1}{4}$, or $3\frac{1}{4}$ sec. from the start it is passing through the same point *in the same direction.* Similarly for all points it passes through. The positions it occupies occur periodically in space and time.

Suppose now to the vibrating pendulum is imparted another motion, and that it is moving in a direction at right angles to the plane of its vibration—like the clock in the *Ingoldsby Legends.* The path traced out by the central point A of the bob will be a wavy line. A complete wave will be traced every second. If the newly imparted velocity is 60 miles an hour, the wave-length will be 88 ft. and the number of moves traced—the *frequency*—will be one per second. Suppose it makes ν vibrations per second, and its velocity is v, the wave-length λ is given by

$$\nu\lambda = v; \quad \therefore \lambda = \frac{v}{\nu}.$$

The wave-length is inversely proportional to the frequency. The perpendicular distance from the crest of a wave to the line of direction along which it advances is the amplitude.

The position of any point along the curve can be indicated by a perpendicular let fall from the point to the line CD (fig. 61). This line is of definite length and direction (it is a *vector*). Those points along the curve of each wave which can be indicated by perpendiculars of equal length and *direction* are said to be in the same phase, e.g. AE, A′E′.

Waves in which these vectors are at right angles to the direction of motion are *transverse*. Huygens suggested

that light was produced by such transverse vibration. His views were strongly opposed. If light travels in straight lines how are transverse waves possible? That was the argument against the wave theory of light.

About 100 years later, Young discovered that light from a given source, on passing through two small holes very close together, gave rise to a series of bright bands with dark spaces between them. This could not be accounted for on the corpuscular theory, but it can be accounted for if light consists of transverse waves.

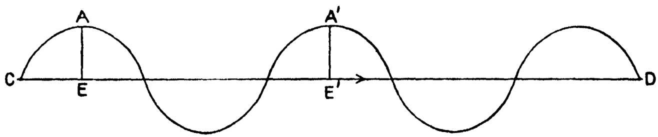


Fig. 61

Let us suppose that two people stand on a bridge over the surface of a perfectly smooth pond. Each drops a stone weighing 1 lb. into the pond. Each stone will agitate the water to the same amount, and a circular wave will travel outwards from it. This wave front will consist of a ridge of heaped-up water followed by a ring of depression in the pond's surface. As they widen the circles will intersect (fig. 62). At points 1, 2, 3, 4, 5, 6 a ridge meets a ridge, consequently the wave crest is doubled in height. At 7, 8, 9, 10 the trough of a wave meets a trough, with the result that the depression is twice as deep. If a trough meets a crest, as at 11, 12, 13, 14, they will neutralize each other (since stones A and B were the same weight and dropped from the same height) and the water will be smooth. Now the waves produced in this case are transverse, and there is a series of bands of exaggerated crests and troughs, alternating with bands of unaltered smoothness of the water. The analogy between the water vibrations and what happens in

Young's experiment is complete. The mutual destruction or enhancement of the two sets of waves is called "*interference*".

The wave theory of light thus became established; it was developed by Fresnel. It was generally believed that light waves were determined by the elasticity of the ether. In order to obtain transverse vibrations in it the

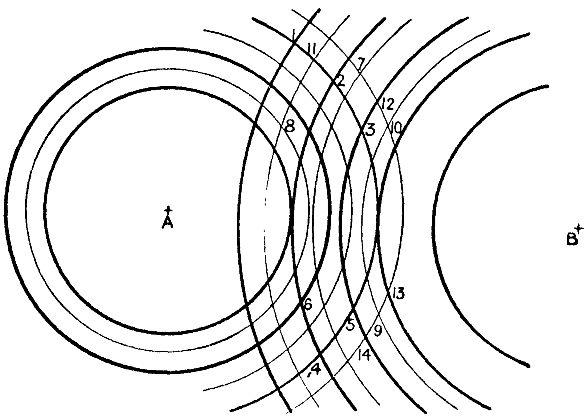


Fig. 62

ether must be solid and incompressible (the latter assuming that longitudinal vibrations are excluded), and yet the ether offers no resistance to the movement of the stars.

In 1873 Clerk Maxwell developed his electromagnetic theory of light. Faraday had shown that currents were induced in conductors when moving in a magnetic field; Maxwell assumed that not only in conductors were such currents induced, but also in insulators and in empty space. Such currents he called *displacement currents*. Such currents should in their turn produce a magnetic field. He proved mathematically the possibility of electromagnetic waves.

We have seen that an electric field can be measured by its effect on unit positive electric charge. This effect at any point is called the field strength. It is a vector quantity and can be represented in magnitude and direction by a line. Suppose at a given point in space such a field varies *periodically*. We shall get electric oscillations, and a corresponding variation in the magnetic field due to the current.

We have seen that the discharge of a Leyden jar consists of a series of oscillations. Electromagnetic waves are sent out through the dielectric of the air. Suppose we could at a given instant of time stop the oscillation and the wave transmission, keeping the waves suspended in mid-air, and then examine the distribution of charge in the dielectric. We should find the maximum points of charge at the crests of transverse waves. The magnetic field would have vanished since there would be no movement of electricity. Note that no movement of the medium takes place; an alternation of *condition* of it is carried forward.

We have seen that the magnetic field set up by a current is always at right angles to the current.

The magnetic field strength is at right angles to the electric field strength of a wave, and both are at right angles to the direction of propagation of the wave.

The velocity of electromagnetic waves was found to be the velocity of light. Further, the electromagnetic waves produced by Hertz obey exactly the same laws as light, they can be refracted and reflected and they show the phenomenon of interference.

It appears, therefore, that electromagnetic waves constitute heat, light, wireless waves, ultra-violet rays, and X-radiation. If we include all these in our spectrum it will be of gigantic dimensions. The visible portion of the spectrum lies between 4000 and 8000 Ångström units

(this unit = 10^{-7} mm.); proceeding from red light (8000 units) to violet the wave-length is reduced to one-half and the frequency is doubled. A note with twice the frequency of another is an octave higher than it, so we may regard the visible spectrum as being one octave.

Sir Henry Wood illustrates the musical range of our ears by the " giant scale " of the orchestra. Starting with the lowest notes of the double bassoon the pitch rises through the clarionet and flute to the highest note of the piccolo, a range of eight octaves or so. The range of visible " tones " is far less extensive, though the eye is a more sensitive instrument over its single octave.

The following is a list of the various types of electro-magnetic waves with corresponding wave-lengths.

Wireless waves (waves by electric discharge), 20,000 metres—8 mm.

A gap of three octaves.

Infra-red (0·5 mm.—8000 Ångström units), 8 octaves.

Visible spectrum (8000—4000 Å.u.), 1 octave.

Ultra-violet (4000—16·5 Å.u.), 8 octaves.

X-rays (16·5—1 Å.u.) } 19 octaves.
Gamma rays (1·25—0·003 Å.u.) }

That portion of the giant spectrum which is visible to our eyes, together with the ultra-violet, can be measured by means of an apparatus employing a prism. On passing light through the prism so that the ray within the material of the prism itself is parallel to the base, a maximum separation of the visible colours takes place; the wave-length of the light decreases from red to violet, the less the wave-length the greater the deviation. For ultra-violet light a quartz prism and lens must be used, and its effect is registered upon a sensitive plate. The apparatus shown in figs. 63 and 64 is a spectrometer of the constant deviation type (see p. 175, Experiments).

Light passes through the narrow slit at the end of the

right-hand tube; the slit is placed at such a distance from a lens at the other end of the tube as to make the rays of light parallel on emerging. The parallel rays pass through the constant deviation prism (fig. 65) in the

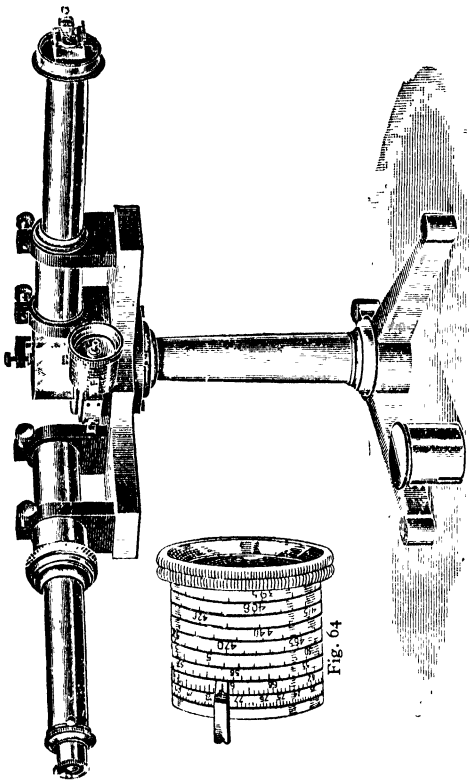


Fig. 63

Fig. 64

Figs. 63 and 64.—Constant Deviation Spectrometer

direction ABCDE. It is totally reflected in the prism at C and finally emerges at right angles to AB. The telescope tube is fixed rigidly at right angles to the tube carrying the slit—the collimator. The prism is moved 'round by the milled head upon which wave-length readings are

etched. So that each ray as it comes under inspection is in position of minimum deviation, i.e. parallel to the line FG. (See experiments.)

We must consider another method by which the visible spectrum may be obtained and by which the wave-lengths of the different colours may be obtained—the method of diffraction.

In 1665 Grimaldi showed that light admitted into a darkened room through a very narrow slit can spread

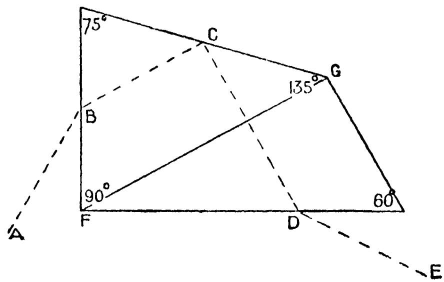


Fig. 65

out in all directions; in other words, light can bend round corners. This spreading out he called diffraction. Suppose now a great number of lines is ruled upon the polished surface of a metal, there being scratched with a diamond point 15,000 lines to the inch. If light is shone on to the " grating ", as it is called, it will be reflected in a regular manner from the spaces between the lines, but from the surface of the scratches themselves it will be scattered.

Suppose a parallel beam of light from the source S falls upon the grating ABCD (fig. 66). AB represents a strip of the polished surface, and BC a ruled scratch in section, made with the diamond. The incident beam makes an angle ι with the normal AR. A portion of

the light is diffracted towards X. Draw perpendiculars DK and BN to incident and diffracted rays. The ray SB reaches K at the same time as SD reaches a diffracting surface D. It has KB distance farther to go before reaching surface B.

But the diffracted ray DX has a longer journey to go than BX before reaching the eye, by the distance DN. These distances BK and DN are called the *retardation.*

The total retardation for the ray SBX on the ray SDX = BK − DN. The distance BD, i.e. the space occupied by a ruled line and a plane surface, is the grating space *b*. Now BK = $b \sin\iota$ and DN = $b \sin\theta$, therefore the total retardation of two successive rays is $b(\sin\iota - \sin\theta)$. If this distance is equal to an odd number of half wave-lengths, the waves, on arriving at the eye, will be in opposite phase and will neutralize each other. If the distance is one or more whole wave-lengths, i.e. an even number of half wave-lengths, the waves will reinforce each other and a bright image is seen. Generally, $n\lambda = b(\sin\iota - \sin\theta)$.

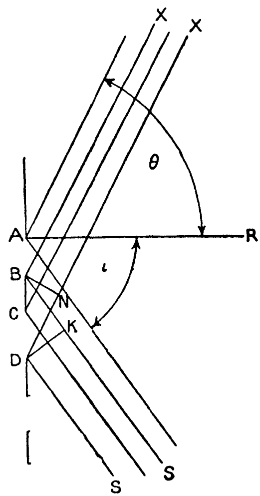


Fig. 66

If we looked at the diffraction of one-coloured light from a grating we should see a bright central band with a series of dark and bright bands. In the case of white light we see the bright central line and next to it the violet, then the colours in their order of increasing wave-length. Since the wave-lengths differ for the different colours, the total retardation (see above)

between any pair of consecutive diffracted rays need not be a constant but must vary for the different wave-lengths; it will vary with the value of the angles of incidence and diffraction. To give the colour it must be one or more whole wave-lengths of that colour. The red, orange, and yellow of the spectrum are well separated with a grating and not crowded together as in the prism spectrum.

The principle of the diffraction grating is of great importance, as it gives a means of determining the wave-length, a method which has been applied to the determination of the wave-length of X-rays.

If we examine the spectrum of incandescent sodium vapour we see, instead of the gorgeous colours of the rainbow, two bright yellow lines very close to each other. Such line spectra (given by the metals in an incandescent state) have an origin which for long was very little understood. Lorentz had suggested that they were caused by the electromagnetic radiation of the electrons contained in the atoms of the metals. If these electrons rotate in orbits around the atom the electromagnetic field will vary periodically and transverse waves of light will be sent out—light of a definite frequency corresponding to the spectral lines.

In 1896 Zeeman discovered that if the sodium incandescent vapour was placed between the poles of a powerful electromagnet, the lines of its spectrum were separated more widely. Further experiment fully supported the Lorentz theory. There is strong evidence for believing that light is due to the vibrating electrons.

But what do we do to produce light? Even in an efficient electric lamp, 95 per cent of the energy consumed is wasted in producing heat, and not light. In order to stimulate the electromagnetic waves sent out by the electrons we have recourse to clashing together millions

of molecules with enormous force in the hope that the electrons, $\frac{1}{10000}$ of the size of an atom, may hasten the journey round their orbits. The glow-worm and the fire-fly manage things better. Phosphorescence and fluorescence appear to be capable of producing light without heat.

Experiments

1. *Wave-length.* A vibrating rod, provided with a brush filled with ink and fixed at right angles to its length, produces a trace upon a moving paper beneath it. A Fletcher's Trolley apparatus is suitable on varying the weight attached to the trolley. The relation between frequency, wave-length, and velocity can be shown. Very nearly uniform velocity can be obtained by allowing the weight to pull the trolley for a few inches, then arresting the fall of the weight; the trolley will move on with nearly uniform velocity (the base of the apparatus is slightly raised to compensate for the friction of the trolley wheels).

2. *Deviation of Light caused by a Prism.* Place a triangular prism upon a sheet of white paper, its triangular face next to the paper. Look through the prism at a distant pin fixed in the paper. The pin will appear to be displaced away from the base of the prism. On rotating the prism this displacement will diminish up to a certain point, when the pin will appear to stand still and then move in the opposite direction in which the prism is rotated. This position in which the pin stops is the position of minimum deviation, in it the coloured border round the pin is the brightest. ABCD is path of the ray from the pin A to the eye at D in the position of minimum deviation (fig. 67). Trace out this ray by fixing pins which appear to be in line at B, C, and D. The angle DEF is the angle which the deviated ray makes with the undeviated ray produced—the angle of *minimum* deviation is obtained when BC is parallel to the base of the prism. This is the position of the prism of a spectrometer when in use.

3. Compare by a spectroscope or spectrometer the spectra obtained (1) from an arc lamp, (2) from sunlight, (3) from a bunsen flame in which a piece of asbestos soaked in brine is being heated on a platinum wire, (4) as in (3), using instead of

brine (*a*) potassium chloride or nitrate, (*b*) calcium chloride solution.

4. Look through a silk handkerchief at the glowing filament of a gas-filled lamp. Coloured bands owing to diffraction appear.

5. Hold a narrow slit horizontally and just above the surface

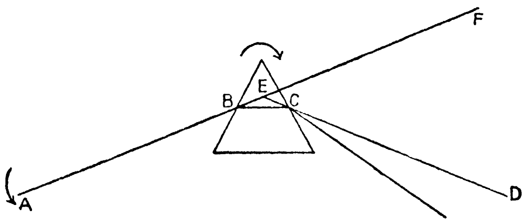


Fig. 67

of a long piece of glass (3 in. by 30 in.). Mount a lens at the other end of the glass. If the slit is illuminated by the sodium flame, dark and bright interference bands are seen. The light direct from the slit to the lens and the light reflected from glass to lens cause interference phenomena.

CHAPTER XIV

THE NUMBERING OF THE ELEMENTS

The Periodic Classification of the elements, for all its convenience, is not fully satisfactory. Even as a system of classifying the properties of elements it has its failures, although they are few compared with its triumphs. When, however, we try to get at the meaning of the system, at the principle behind it, we find it hard to believe that the atomic weight is the most intimate property of the atom. The fundamental importance of atomic weight was in doubt even before the discovery of isotopes, but the death-blow was given by the knowledge that atoms of

different weight might have identical chemical properties.

What then is the fundamental property? What is it that makes an atom of mass 36 almost identical in properties with an atom of mass 40, yet so different from an atom of mass 39? These questions lead us to the still deeper one—What is the nature of atoms?

The expulsion of α- and β-particles from radio-active elements leads us to expect that atoms are electrical in character. They must contain both positive charges and electrons. How are these charges arranged within the atom? The only hypothesis that has survived is that every atom consists of a positive nucleus with satellite electrons whirling round it. The difference between atoms, e.g. between an atom of hydrogen and an atom of gold, lies in the number of positive charges on the nucleus and the (equal) number of satellite electrons.

From experiments on X-rays Barkla was able to obtain an estimate of the number of satellite electrons in some atoms. The number was approximately half the atomic weight. Now the number of the place an atom occupies in the periodic system is also about half the atomic weight. Thus the 26th element, namely iron, has an atomic weight 55·84. Van den Broek suggested in 1911 that the number of satellite electrons in an atom was the same as the number of its place in the periodic system. On this hypothesis, an atom of hydrogen consisted of a positively charged nucleus and a single whirling electron. The nucleus of the next atom, helium, bore a double charge of positive electricity and had two satellite electrons. The lithium atom had three electrons, the beryllium atom four, and so on. The thirtieth element in the periodic system, namely zinc, had thirty electrons revolving round a nucleus which bore thirty positive charges. The charge on the nucleus is conveniently called the atomic number of the element.

It was not possible to find by direct experiment either the charge on the nucleus or the number of electrons. Atomic numbers could be assigned to elements only on their position in the periodic system. We could say that the atomic number of aluminium was 13, and that of bromine 35. The 43rd element was missing, but Mendeléef had left a place for it, so atomic numbers could be given to all the elements up to barium (56). Further it was not safe to go, for after barium came the rare earth metals. The periodic system had failed to predict the number of these metals, and it was impossible to say how many remained unknown. Atomic numbers could be assigned neither to them nor to any of the elements that came after them.

The experimental investigation of atomic numbers by H. G. J. Moseley is one of the most interesting pieces of research of modern times. The work was published in 1913 and 1914, just before the outbreak of the Great War, in which the brilliant young scientist was killed in action.

Moseley's method depended on the examination of spectra formed by X-rays. We know that X-rays are similar to light rays in nature, but are about 5000 times shorter in wave-length. They vibrate 5000 times faster than light rays and the distance between successive waves is correspondingly reduced. Now light waves are spread out into a spectrum by a diffraction grating if the distance between the rulings of the grating is about the same as the wave-length of light. X-rays would hardly detect the rulings of an ordinary grating. They would require at least 1000 times as many lines to the inch before they would form a spectrum. The hopelessness of attempting to rule a grating of such fineness is obvious when it is realized that the distance between the lines would have to be little more than the diameter of a single molecule.

We cannot, then, rule a grating. We can do better, and find one ready made. Workers upon the structure of crystals had been led to suppose that the molecules in a crystal were arranged in an orderly manner. The molecules were supposed to be regularly arranged in space in such a way that there were planes of closely packed atoms parallel to the faces of the crystal. Here was a chance of testing the hypothesis of the crystallographers, and, if it were true, of obtaining an X-ray spectrum.

This suggestion, due to Laue, of using a crystal as a diffraction grating has had two important developments. It has enabled Sir William and W. L. Bragg to investigate the structure of crystals, and it enabled Moseley to examine X-rays. The Braggs use X-rays from the same source on different crystals, and Moseley used one crystal to examine X-rays from different sources.

Moseley obtained spectra of the X-rays produced when different metals were used as anti-cathodes in an X-ray tube. The spectra were all different. Hence it followed that each metal when bombarded by the stream of electrons from the cathode gave out its own particular kind of X-ray. The difference between the X-rays from, say, iron and those from copper was one of frequency and so also of wave-length. They were therefore reflected at different angles from the face of the crystal, just as red light and blue light are reflected at different angles from a ruled grating.

An X-ray spectrometer is shown diagrammatically in fig. 68. The X-ray tube is enclosed, for protection of the operator, in a lead box L, but the rays are allowed to come out by a small window of aluminium (W). A narrow pencil of rays is selected by the cylindrical tube T_1 and is then reflected from the crystal C through a second tube T_2 on to a photographic plate P. The

inclination of the crystal to the rays may be read on the scale at S, on the end of an arm from the crystal table.

In Moseley's experiments the metals to be tested were mounted on a trolley inside the X-ray tube. The trolley was drawn along by a magnet held outside the X-ray tube so that one metal was substituted for another as anti-cathode. In this way each metal was bombarded by cathode rays of the same " hardness ".

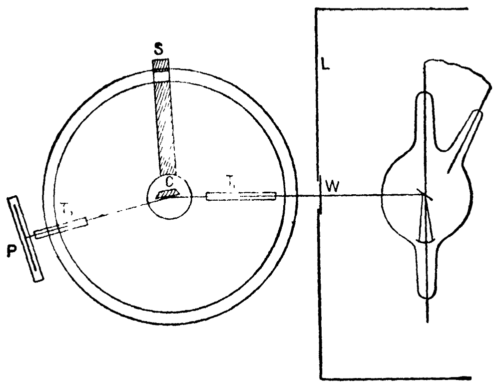


Fig. 68

Some of the spectra obtained are shown in fig. 69, which is taken from Moseley's original paper. They are arranged so that lines due to rays of the same frequency are vertically over one another. There are several points worth notice. First, the spectra are very much simpler than most light spectra; those shown in the diagram consist of only two lines each. The spectrum of cobalt shows lines due to iron and nickel both of which are commonly found in cobalt as impurities. Brass is an alloy of copper and zinc, so the spectrum shows the rays from both these metals.

The metals are in the order in which they follow one another in the periodic system, except that scandium, which lies between calcium and titanium, was not used on account of its scarceness. It is obvious that there is a regular shift of the lines as we pass from element to

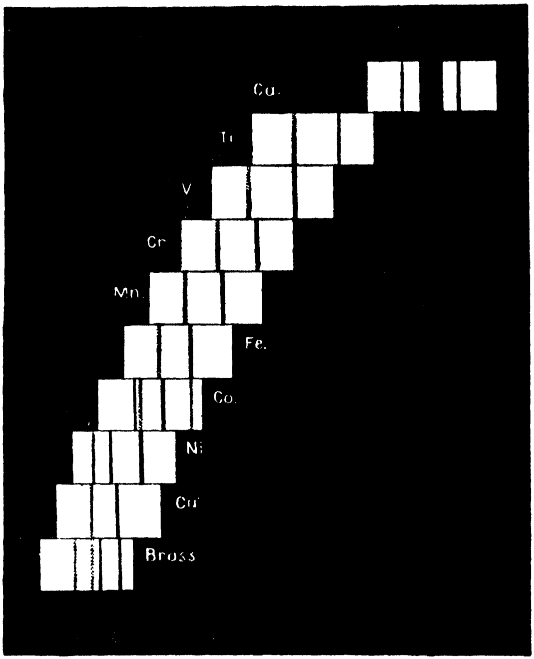


Fig. 69.—X-ray Spectra

element, and the position of the scandium lines could be foretold from the positions of the others. As Moseley said, "We have here a proof that there is in the atom a fundamental quantity, which increases by regular steps as we pass from one element to the next."[1]

[1] *Phil. Mag.*, XXVI, p. 1031 (1913).

The direction of the shift of the spectrum lines shows that as the atomic number of the elements increases the frequency of the waves increases also. (That is, the X-rays from elements early in the periodic series are of longer wave-length than those from elements later in the series.) The lines themselves do not shift by an equal amount each time we pass from one element to the next. That is, it is not the frequency that increases by an equal amount each time, but, in fact, the square-root of the frequency.

For the simplest lines the following equation was found to be true:

$$\sqrt{\frac{\text{frequency}}{\text{a constant}}} = Q,$$

where Q is a quantity which increases by an even amount as we pass from element to element. The actual value of Q for each element depends on the value of the constant in the equation. We must, of course, keep the same constant for all elements in the series, but by altering its value throughout we alter the value of Q throughout. Thus when the constant is multiplied by 9 the value of Q is reduced to $\frac{1}{3}$ of its former value. If this is done for all elements then Q will still increase evenly from element to element, but the amount of the increase will be $\frac{1}{3}$ of what it was before.

By choosing a suitable value for the constant, Q for each element came out very nearly a whole number and increased uniformly by one for each successive element. Thus Q for calcium was 19·00, for titanium 20·99, for vanadium 21·96, and so on. These numbers are each one less than the atomic number previously suggested for the elements. Therefore, to find the atomic number of any element in the series it is sufficient to find the frequency of one of the X-rays given by the element

and to perform a simple arithmetical calculation.

But has the equation any theoretical justification? or is it merely a chance relation between the frequency and the atomic number? The clue obviously is to be found in the constant. Now that we have settled what its value is to be, do we recognize it as a fundamental number, or do we find that it is an arbitrary number, like the number of inches in a metre? The answer is that the constant has a meaning and is not an accidental number.

If in the above equation we substitute "reciprocal wave-length" for "frequency" (that is if we divide the frequency by the velocity of the waves, see p. 166), then our constant is $\frac{3}{4}$ of the Rydberg constant which appears in the equations connecting the reciprocal wave-lengths of the lines in ordinary light spectra. The Rydberg constant is derived from the wave-lengths of the lines in the hydrogen spectrum, and represents 109,677·6 waves to the centimetre.

It is as though we had been aware that the circumference of a circle was 3·14159 times its diameter, and now found that its area was 3·14159 times the square of the radius. The Rydberg constant is a fundamental constant of spectra just as π is a fundamental constant of the circle.

Moseley was thus able to determine experimentally the atomic numbers of many elements. The heavier elements gave spectra slightly more complicated than those shown in fig. 69, but they are connected by laws of the same type as those that govern the simple spectra. It has been possible, therefore, to find the atomic numbers of elements in all parts of the periodic system.

What has been the effect of Moseley's work on the Periodic System? Firstly, it has justified the system. In itself it does not explain the recurrence of properties,

but it does provide us with an atomic order. We no longer have to weigh up the claims of atomic weight and of chemical properties to be the basis of the sequence of the elements. It is interesting to note that the order based on chemical properties agrees with that based on the atomic numbers. The atomic number of cobalt is one less than that of nickel, although its atomic weight is higher. Similarly argon has a lower atomic number than potassium, and tellurium than iodine. The "anomalies" of the periodic system have been accounted for.

Secondly, the determination of atomic numbers has told us how many elements lighter than uranium remain to be discovered. There may be elements heavier than uranium. Or it may be that such elements, if they ever existed, have already disintegrated into uranium and other elements. However this may be, we know that there are only 91 atomic numbers lower than that of uranium (92), and presumably, therefore, only 92 elements in all, including uranium.

Not the least of the results of this knowledge is that it tells us how many rare earth metals there are. The atomic number of barium is 56 and that of tantalum 73, so there can be only 16 elements between them.

How many elements are missing? In 1914 there were six vacant spaces in the system. Elements of atomic number 43, 61, 72, 75, 85, and 87 were unknown. In 1923 element No. 72 was discovered and named hafnium. Its properties are not those of the rare earth metals, so it must be given place No. 72 to itself. The rare earth metals are therefore fifteen in number, all crowded into one place in the system. These metals are not isotopes; each has its own atomic number varying from 57 to 71, but there is only one place in the system for all of them. The periodic system still fails to account for these

elements. The search for the remaining rare earth metal, No. 61, has, so far, been fruitless.

Elements Nos. 43 and 75 must from their positions in the table be members of the manganese family. A definite search for these elements has been made by Noddack and Tacke. Platinum ores containing elements 44 to 47 and 76 to 79, and the mineral "columbite" which contains elements 39 to 42 and 71 to 74, were examined. From columbite was obtained, in 1925, 0·05 gm. of material which gave X-ray spectra corresponding to the elements 43 and 75. Until a larger quantity of the elements is obtained we cannot know much of their properties, but it is fairly safe to say that elements 43 and 75 have been discovered. The suggested names are masurium and rhenium.

Elements Nos. 85 and 87 must almost certainly be radio-active, if they exist. It is quite possible that they are never produced in the disintegration series. The atomic structure required may possibly be too unstable to be formed. Whether this is so or not it is impossible to say. All we can say is that the search for evidence of the existence of these elements has so far been unavailing. There are therefore three elements lighter than uranium, namely Nos. 61, 85, and 87, at present unknown.

Moseley's work is one of those "keystone" researches which unite and make firm the structures that have been built up from different directions. From the crude attempts to classify elements we had arrived at the periodic system. From the study of the passage of electricity through gases at a low pressure, we passed to cathode rays and thence to X-rays. From X-rays we came to know of radio-activity, the facts of which led to the hypothesis of a nuclear atom and so to the idea of atomic number. The study of crystals had led to an hypothesis of their structure, which was verified by the production

of an X-ray spectrum. X-ray spectra tell us atomic numbers, and the atomic numbers justify the periodic system.

Though the details may be elaborate there is a simplicity in the whole, and there is beauty in that simplicity. To Moseley belongs the credit of supplying the finishing stroke to the work in which many have laboured.

The finishing stroke? Only in a limited sense. The completeness of our knowledge in this branch of science is not for contemplation only. It gives us a firmer foothold so that we may press on farther. What is the meaning of atomic number? Is it equal, as van den Broek supposed, to the charge on the nucleus? What is the reason for the recurrence of similar properties at intervals in the series of elements? In what point of structure does one isotope resemble another that their properties should be so much alike?

CHAPTER XV

THE STRUCTURE OF THE ATOM

In this chapter an attempt will be made to sum up the views on the structure of the atom which have developed from the work discussed in previous chapters. To consider all the evidence is beyond the scope of this book, and we must be content to describe the atom as now pictured and to ascribe to the various parts of it the different properties which we associate with matter.

It cannot be too clearly stated that our opinions on the nature of the atom are not dogmatic creeds or articles of belief, but hypotheses which may need at any time to be modified. True, the hypotheses are sufficiently well supported by evidence to encourage us to hope that any change will be only a modification and not a complete

overthrow. It seems unlikely, but it is not impossible, that we shall have to witness what Huxley called "the great tragedy of science—the slaying of a beautiful hypothesis by an ugly fact".

We have seen that it has been necessary to assume that the atom consists of a central nucleus surrounded by whirling electrons. For an electrically neutral atom the charge on the nucleus must be the same as the number of satellite electrons, and this number we call the atomic number of the element. Hydrogen is supposed to consist

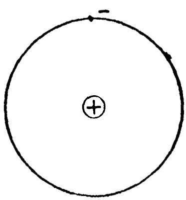


Fig. 70.—Hydrogen Atom

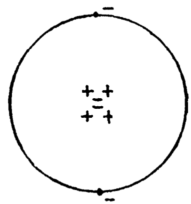


Fig. 71.—Helium Atom

of a singly charged nucleus and a single electron. Since the electron weighs only $\frac{1}{1800}$ of the whole atom, we may take it that the whole of the mass of the atom is possessed by the nucleus. The mass, therefore, of the hydrogen nucleus (also called the "proton") is approximately 1.

Following Professor Soddy, we may imagine the hydrogen atom magnified to the size of the earth. The diameter of the orbit of the electron would then be 8000 miles, the diameter of the electron itself would be 500 yards, and that of the nucleus would be 1 foot. These diagrams are not drawn to scale.

The atom of helium has a nuclear charge 2, so it might be taken to consist of two protons. But it has a mass 4, so it must contain four protons. To get over this discrepancy we have to suppose that it contains four protons, thus making its mass 4, and also two electrons, which

do not appreciably affect the mass but which reduce the net charge on the nucleus to 2. The helium atom therefore consists of four protons and two electrons in the nucleus, and two electrons revolving round the nucleus.

We can apply this argument to all atoms. For instance, uranium has an atomic weight 238, and an atomic number 92. To account for its mass we suppose the nucleus contains 238 protons, and to reduce the nuclear charge to 92 it must also contain 238 — 92, i.e. 146 electrons. Outside the nucleus there will be, of course, 92 electrons.

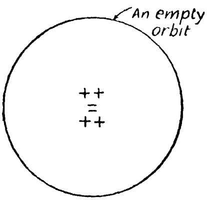


Fig. 72.—α-particle

Of the arrangement of these protons and electrons within the nucleus we have very little knowledge. We do know, however, that the helium nucleus, consisting of four protons and two electrons, is a very stable system, and we have reason for believing that it exists as such within the nucleus of other atoms. The evidence is twofold. First, it is expelled as a unit in itself during radioactive change. It is then called an α-particle, and being without the two satellite electrons the atom as a whole bears a double positive charge. Second, by vigorous bombardment Rutherford has torn off protons from some atoms, but only from those atoms which contain more protons than can condense to form helium nuclei (see also p. 160).

If we assume that both the α- and the β-particles expelled during radio-active change come from the nucleus, the production of isotopes is readily explained. If an α-particle is lost from the nucleus the mass is reduced by 4 and the net charge on the nucleus is reduced by 2. As the nuclear charge is reduced by 2 the atomic number is reduced by 2. That is the new atom occupies a place two to the left of that occupied by the original

atom (cf. p. 154). If it loses a β-particle, that is an electron, from the nucleus the atomic number is increased by 1, and the element moves one place to the right. If from the same nucleus are lost successively one α- and two β-particles the net charge returns to its original value. That is, the atomic number returns to its original value. Thus the atomic number of uranium I is the same as the atomic number of uranium II; the charge on the nucleus is the same, and the number of satellite electrons is the same. The only difference is in the nucleus, that of uranium II having four protons and four electrons less than that of uranium I.

If this is a true picture, then, since uranium I and uranium II have identical chemical properties, we must conclude that chemical properties are not determined by the nucleus, for the nuclei differ. They must be determined either by the nuclear charge or by the satellite electrons. The only hypothesis which fits the facts is that the chemical properties originate in the outermost electrons.

We speak of outermost electrons, for the satellites are not all at the same distance from the nucleus. It is supposed that the lithium atom is arranged like the helium atom, except that its nuclear charge is greater by one unit, and that a third satellite electron has an orbit outside the two of helium, as in fig. 73.

The next atom, beryllium, has two electrons in the outer ring, boron three, and so on up to neon, which has eight.

After neon a third ring is started by sodium. This ring, like the second, can accommodate eight electrons. The ninth element farther on, namely potassium, starts a fourth ring. There is doubt how many this fourth ring can accommodate, but it is generally agreed that the fourth and fifth rings together can hold eighteen, so that the sixth ring is started by rubidium.

In this arrangement elements of the same family, that is elements with similar properties, have the same number of electrons in the outermost orbit. Thus lithium, sodium, potassium, and rubidium each have one electron in the outermost orbit. To this common factor may be ascribed those properties which belong to all the members of the family, while the different number of completed rings between the nucleus and the outermost ring will

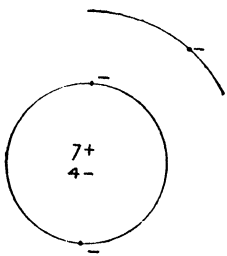


Fig. 73.—Lithium Atom
Atomic number 3.
Atomic weight 7.

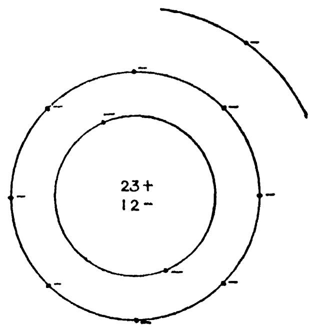


Fig. 74.—Sodium Atom
Atomic number 11.
Atomic weight 23.

account for the regular variation in properties between the elements in the group.

When a ring is complete it cannot easily be broken up. The argon gases are supposed to have completed rings only and these atoms are very stable structures. The elements which immediately follow them, however, each have a solitary electron outside the complete rings, and this electron is apt to get lost. If it is lost then the nuclear charge is not completely neutralized, and the atom as a whole is positively charged. Thus an atom of sodium readily becomes the sodium ion of electrolysis (Chap. IX). It was always difficult to see how an atom

of the very active metal sodium could exist in solutions. So long as it was positively charged it remained inactive, but when that charge was neutralized at the electrode, it became the familiar active atom of sodium. We now see that its activity is due to the single electron in the most distant orbit. When that electron is lost there is a complete ring of eight on the outside, so the atom is not chemically active.

What becomes of the lost electron? Suppose the salt dissolved in water is common salt, sodium chloride. The chlorine atom has only seven electrons in the outermost ring. It prefers to have either eight or none at all. If it takes the spare electron from the sodium to complete its own ring it will form a stable arrangement, resembling in external structure the next element, namely argon, but, of course, its nuclear charge is one less than that of argon. The chlorine ion is thus negatively charged. When it delivers up its extra electron to the anode it becomes an ordinary atom of chlorine, and comes off as a gas.

We thus get a picture of ionization of salts in solution and also of valency. If, like sodium, an atom has a single electron in the last orbit it will be a " univalent metal "; if, like chlorine, it has seven atoms in the last orbit it will be a univalent non-metal. On our hypothesis copper has two electrons in the last orbit. If both these are lost the atom is bivalent, if only one it is univalent. Oxygen, on the other hand, wants two electrons to complete its last ring, and it appears never to be content with one. The two electrons may come from the same atom of metal as when one atom of copper combines with one atom of oxygen, or they may come from separate atoms as when two atoms of sodium combine with one of oxygen.

As explained in Chapter X, the ionization of gases consists of the forcible removal of one of the outer elec-

trons. The separated electron and the remainder of the atom constitute the negative and positive ions respectively.

Many other properties are explained by this model of the atom. The metals are those elements whose atoms have easily-lost electrons on their outside. If we suppose that these atoms can be passed from one atom to the next we have a picture of the passage of an electric current. If we imagine them free enough to vibrate apart from the vibration of the rest of the atom we may have an explanation of the peculiar lustre of metals.

The nucleus, then, is responsible for the mass and for the radio-active properties of an atom, and the incomplete ring for the chemical and some of the physical properties. The completed rings are held to give rise to spectrum lines. The lines of the hydrogen and helium spectra have been accounted for on the assumption that the atom is constructed on the above hypothesis. The X-ray spectra are supposed to arise from the vibration of electrons in the innermost rings, and light spectra from vibrations in the larger rings farther away from the nucleus.

A word of warning is necessary. We cannot yet draw a picture of an atom. The most we can attempt is to draw a diagram. As fresh evidence is brought to light our diagram needs modification. The diagrams given earlier in this chapter have already been shown to be inadequate. In order to explain the spectrum lines it is necessary to assume that the orbits of the satellite electrons are not circles but ellipses. Again, our diagrams are usually plane figures, but there is every reason to suppose that an atom has three dimensions, that is that the orbits do not all lie in the same plane. As mentioned in the chapter on Scientific Method, it is only by sifting all the evidence, by constant search for more evidence, and by impartial pruning of hypotheses that we can approach nearer to truth.

But what is the value of these hypotheses to "the man in the street"? Is it not rather like talking to him about "shoes and ships and sealing-wax and cabbages and kings"?

No, for the theories of the laboratory to-day and the discoveries to which they lead are in the workshop to-morrow. There are many instances which support this statement. The corpuscles of Sir William Crookes and the electrons of Dr. Johnstone Stoney were a few years ago hypothetical particles; they are now the recognized unit of electricity. The wireless enthusiast uses them nightly, as well as the electromagnetic waves the possibility of whose existence was recognized by the genius of Clerk Maxwell.

The existence of ultra-violet rays and their ionizing power was, in the first place, recognized by the work of trained specialists in the laboratory. Thirty years ago in the smoke-laden atmosphere of manufacturing towns there was no thought of the beneficial aid of these rays in the prevention of disease and the development of healthy bodies, though to-day it is fully recognized. The ultra-violet rays are available in child welfare centres, in hospitals, and even in private houses. The advancement of Science is very much the affair of every man. It is the business of us all to recognize that the discoveries of her men of genius are the birthright of the nation.

TABLE OF THE PERIODIC SYSTEM

Period No.		Group o.	Group I.	Group II.	Group III.	Group IV.	Group V.	Group VI.	Group VII.	Group VIII.		
I	Hydrogen 1·008	Helium 4·00	Lithium 6·94	Beryllium 9·02	Boron 10·82	Carbon 12·00	Nitrogen 14·01	Oxygen 16	Fluorine 19·0			
II		Neon 20·2	Sodium 23·00	Magnesium 24·32	Aluminium 26·97	Silicon 28·06	Phosphorus 31·027	Sulphur 32·064	Chlorine 35·46			
III		Argon 39·91	Potassium 39·096	Calcium 40·07	Scandium 45·1	Titanium 48·1	Vanadium 50·96	Chromium 52·01	Manganese 54·93	Iron 55·84	Cobalt 58·94	Nickel 58·69
			Copper 63·57	Zinc 65·38	Gallium 69·72	Germanium 72·6	Arsenic 74.96	Selenium 79·2	Bromine 79·92			
IV		Krypton 82·9	Rubidium 85·44	Strontium 87·63	Yttrium 88·9	Zirconium 91·0	Niobium 93·1	Molybdenum 96·0	Masurium ?	Ruthenium 101·7	Rhodium 102·91	Palladium 106·7
			Silver 107·88	Cadmium 112·41	Indium 114·8	Tin 118·70	Antimony 121·77	Tellurium 127·5	Iodine 126·93			
V		Xenon 130·2	Caesium 132·81	Barium 137·37	Rare Earth Metals	Hafnium 178·6	Tantalum 181·5	Tungsten 184·0	Rhenium ?	Osmium 190·8	Iridium 193·1	Platinum 195·23
			Gold 197·2	Mercury 200·61	Thallium 204·39	Lead 207·20	Bismuth 209·00	Polonium (210)	?			
VI		Niton 222·0	?	Radium 225·95	Actinium	Thorium 232·15	Proto-actinium	Uranium 238·17				

The atomic weights are given, to two decimal places, from the International Atomic Weights of 1925.

APPENDIX

The Whole-number Rule

The departure of Hydrogen from the " Whole-number Rule " has been explained on the assumption that matter can be converted into energy. It is supposed that if four hydrogen atoms condensed to form one helium atom a large amount of energy would be set free and a small decrease in mass would result. The mass of hydrogen atoms would therefore be slightly more than one fourth of the mass of a helium atom.

With improved apparatus with which he can measure atomic masses to one part in 10,000 Aston finds that the masses of some other atoms differ slightly from whole numbers. For example, nitrogen atoms have a mass 1 ·008, oxygen (16) still being the standard. Fluorine even to the higher degree of accuracy has a whole-number mass, 19·000. Boron (11·0110) and helium (4·00216) both have extra fractions. The atomic mass of hydrogen is now given as 1·00778.

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